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A Lightweight Vibration Monitoring System for the S-70A-9 Black Hawk Transmission

D.M. Blunt and S.A. Dutton

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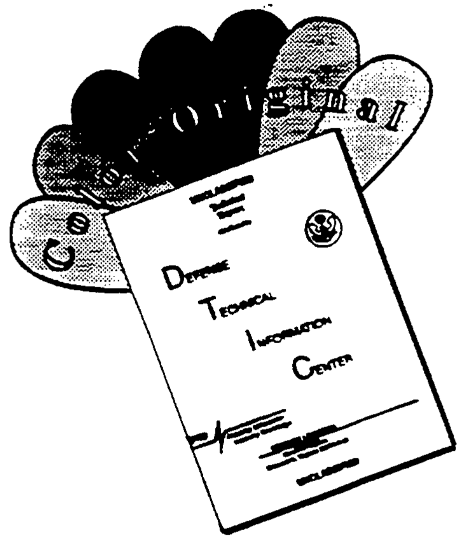

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D.M. Blunt and S.A. Dutton

Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

A lightweight carry-on/carry-off transmission vibration monitoring system has been developed for the Black Hawk helicopter. The system collects vibration data from accelerometers mounted on the transmission while in flight, and then post-processes the data on the ground using AMRL-developed fault detection algorithms. This report describes the system, its installation and operation, and the results of a flight trial conducted by the RAAF Aircraft Research and Development Unit.

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A Lightweight Vibration Monitoring System for the S-70A-9 Black Hawk Transmission

Executive Summary

The transmissions of the Australian Army Black Hawk helicopters are maintained on-condition, that is they have no fixed overhaul life. At present the transmissions are monitored with magnetic plug chip detectors built into the oil scavenge lines of the gearboxes. Limits are set on the number of warnings that can be tolerated from these detectors before the transmission must be overhauled. To supplement the warnings from the chip detectors, and thereby improve the operational safety of the aircraft, the Aeronautical and Maritime Research Laboratory (AMRL) has undertaken the design and development of a lightweight vibration monitoring system for the Black Hawk transmission.

This report documents the system, its installation and operation, and the results of a flight trial conducted by the RAAF Aircraft Research and Development Unit (ARDU) in October 1995. The system has been constructed around a small ruggedised portable computer. It incorporates two commercially available data acquisition cards plus an AMRL-designed circuit board which provides the necessary signal conditioning for six vibration and two tachometer channels. A connector interface is mounted on the side of the computer housing. Cabling is permanently installed in the aircraft to five accelerometers: one on each input module, one on the main module, one on the intermediate gearbox, and one on the tail rotor gearbox. A tachometer signal for the main rotor gearbox is derived from the 115 VAC power supply, and a tachometer signal for the tail rotor is obtained from a photocell mounted on the top of the tail pylon.

It is envisaged that the system will be carried onto the aircraft at periodic intervals of between 20 to 50 hours. It can be installed within a few minutes, requiring just three cable connections in the cabin roof. Vibration data are acquired during the next flight, and then the computer is removed from the helicopter for data analysis.

The system performed well during the ARDU flight trial. Data were acquired under a number of flight conditions, and the data analysis has identified the most appropriate flight conditions for future transmission monitoring. The system could now be deployed on one or two helicopters at a regiment for an extended field trial. Such a trial would identify any operational or logistic difficulties that might be experienced with frequent use, and enable sufficient data to be accumulated to set appropriate vibration alarm levels for the Black Hawk fleet. The system could also be used on an ad-hoc basis to monitor problem gearboxes on other aircraft, such as those producing chip warnings, enabling a fault database to be built up.

Authors

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Mr Blunt graduated from the University of Western Australia in 1989 with a Bachelor of Engineering (Mechanical) degree with first class honours. He commenced employment with the Aeronautical and Maritime Research Laboratory in 1990 and spent two years in the engineer rotation scheme. Since 1992 Mr Blunt has been working in the field of machine dynamics, and in particular the use of vibration analysis for gearbox fault detection. He has been involved with a number of in-flight and test cell vibration trials conducted on fixed and rotary wing aircraft transmissions operated by the Australian Defence Forces.

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Mr Dutton graduated from the University of Queensland in 1985 with a Bachelor of Engineering (Electrical) degree with second class honours. He commenced employment with the Aeronautical and Maritime Research Laboratory in 1986. Since that time he has been working in the field of test cell and aircraft flight trials instrumentation. He has provided instrumentation for various engine test cells including the RAAF F-111 cell at Amberley. He has participated in numerous flight trials, primarily of rotary wing aircraft. These include first of class flight trials with the RAN, rotor track and balance, vibration trials and most recently the investigation of panel cracking on Black Hawk helicopters.

Contents

List of Abbreviations

ADC	Analogue-to-Digital Converter
AMRL	Aeronautical and Maritime Research Laboratory
ArmyLMSQN	Army Aircraft Logistics Management Squadron
ARDU	Aircraft Research and Development Unit
ATIS	Automatic Terminal Information Service
CPU	Central Processing Unit
EMI	Electro-Magnetic Interference
HUMS	Health and Usage Monitoring System
ICP	Integrated Circuit Piezoelectric (accelerometer)
ISA	Industry Standard Architecture
KIAS	Knots Indicated Air-Speed
OAT	Outside Air Temperature
MB	Mega-byte
NSM	Non-Standard Modification
RAAF	Royal Australian Air Force
RAM	Random Access Memory
RAN	Royal Australian Navy
RTVAP	Recorded Tape Vibration Analysis Program
TSN	Time Since New
VAC	Volts Alternating Current
VDC	Volts Direct Current

List of Drawings

AMRL	66537-A1	Fieldworks Gearbox Vibration Analysis - Block Diagram & Cable Diagram
AMRL	65971-A1	Black Hawk Vibration Monitoring System - Circuit Diagram
AMRL	66565-A2	Black Hawk Main Transmission - Accelerometer Mount
AMRL	66566-A2	Black Hawk Intermediate and Tail Rotor Gearbox - Accelerometer Mount
ARDU	KB14B0719	Instl/Assy Strobe Sensor Mount
ARDU	KB14G0708	Instl/Assy Computer Harness
ARDU	KB14Z0707	GA Transmission Vibration Analysis System
ARDU	KB14V0072	Instl/Assy, Modified Tail Boom AN/AAR-47 EW System

1. Introduction

The transmissions of the Australian Army S-70A-9 Black Hawk helicopters are maintained on-condition, that is they have no fixed overhaul life. At present, the transmissions are monitored with magnetic plug chip detectors built into the oil scavenge lines of the gearboxes. Limits are set on the number of warnings that can be tolerated from these detectors before the transmission must be overhauled. To supplement the warnings from the chip detectors, and thereby improve the operational safety of the aircraft, the Aeronautical and Maritime Research Laboratory (AMRL) has undertaken the development of a vibration monitoring system for the Black Hawk transmission.

The development of this system has its origins in the Recorded Tape Vibration Analysis Program (RTVAP) used by the Royal Australian Navy (RAN) on their Wessex and Sea King helicopters [Ref 1]. The RTVAP uses a tape recorder to record in-flight gearbox vibration, and a computer ground station incorporating AMRL-developed fault detection algorithms to analyse the data. The Black Hawk system, however, has been designed to acquire in-flight vibration data directly to a computer, eliminating the need for a tape recorder and a separate ground station. The objectives for this are:

a) to reduce the number of steps between vibration data acquisition and analysis;

b) to remove the problems associated with the operation of a tape recorder in flight; and

c) to simplify the operation of the system.

The initial phase of the Black Hawk system development used a prototype that was constructed from off-the-shelf laboratory equipment housed in an equipment rack. It was test flown in a Black Hawk in July 1993 by the Aircraft Research and Development Unit (ARDU) with successful results [Refs 2 & 3]. Following the trial, the Army Aircraft Logistics Management Squadron (ArmyLMSQN) were keen to proceed with a vibration monitoring program for the Black Hawk, but considered the construction and test of a more compact system a prerequisite.

This report documents a new lightweight vibration monitoring system developed from the earlier prototype, and the ARDU flight trial of this system undertaken in October 1995. The new system has been constructed around a small ruggedised portable computer. Size and weight savings have been achieved by the design and use of an new signal conditioning circuit board, and a compact connector interface for the side of the computer. These replace previously used external components, and eliminate the need for an equipment rack by encapsulating the system within the computer housing. The system is designed for operation with the accelerometers and cables permanently mounted in the helicopter, with the cables terminating at a single multi-pin connector in the cabin roof. The computer is small enough to be strapped to a regular aircraft seat, and can be installed in a few minutes. Vibration data can then be acquired during the next flight, after which the computer is be removed from the helicopter for data analysis.

2. Description of System Hardware

A schematic diagram of the transmission vibration monitoring system is shown in Figure 1. It consists of:

a) a small portable ruggedised computer;

b) data acquisition cards within the computer;

c) a connector interface on the side of the computer;

d) accelerometers mounted on the transmission gearboxes;

e) a tail rotor photocell and photocell processor; and

f) cables to connect the computer to the transducers and aircraft power.

Further details of this hardware are described in the following sub-sections, while details of the aircraft installation, which is spilt into the carry-on/carry-off and permanent installation sections shown in Figure 1, can be found in Section 3.

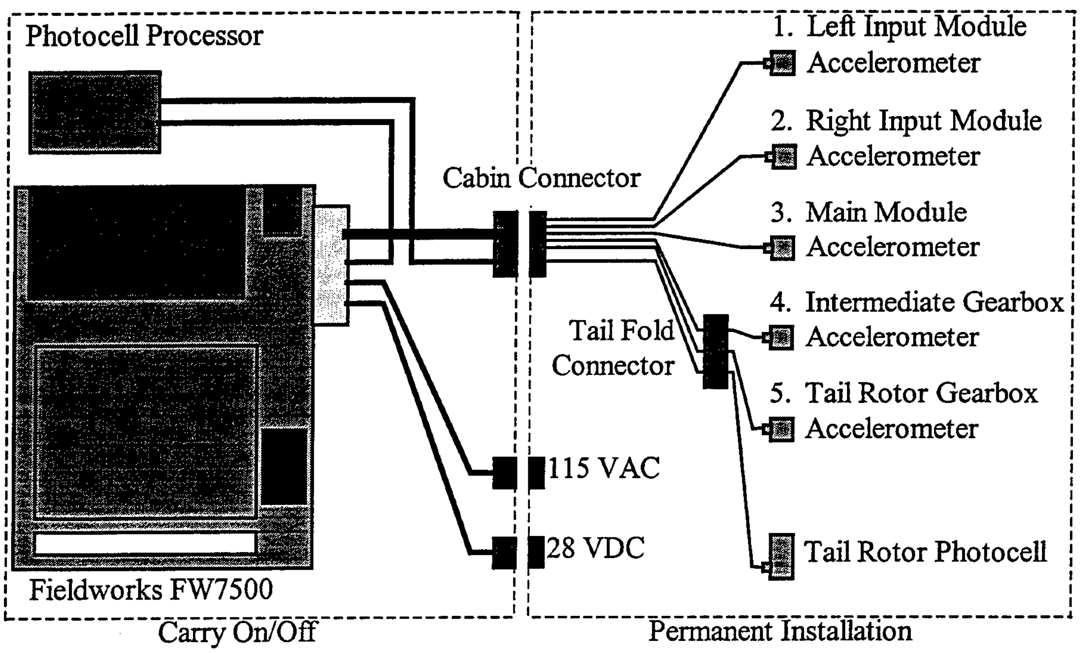


Figure 1. Black Hawk Transmission Vibration Monitoring System Schematic

2.1 Computer

The computer selected for the system is a Fieldworks FW7500. The FW7500 has a 75 MHz 486 CPU, and was fitted with 16 MB of RAM and a 520 MB hard disk. It features [Ref 4]:

a) a rugged one piece magnesium alloy chassis with a rubberised aluminium external skin;

b) shock mounted motherboard and disk drives;

c) three full length Industry Standard Architecture (ISA) expansion card slots, which are used for the data acquisition cards (see Section 2.2);

d) an optional 10 to 30 VDC power supply, which allows the computer to be run from an aircraft 28 VDC power supply in addition to the standard 240 VAC domestic mains supply; and

e) an environmental operating range of 0°C to 50°C, and 10% to 80% relative humidity (non-condensing), and also meets Mil Std 810C (method 516.2, procedure 1) for shock and vibration.

2.2 Data Acquisition Cards

Data acquisition is accomplished with three full length ISA expansion cards: an AMRL-designed signal conditioning card, an anti-aliasing filter card, and an analogue-to-digital converter card. The cards are installed lengthways across the rear of the computer, with the connectors on the right side behind the connector interface. A schematic diagram of the signal paths is shown in Figure 2. The vibration and tachometer signals enter the signal conditioning card at point 1 along individual shielded twisted pair conductors which originate from the rear of the multi-pin connectors on the connector interface (see Section 2.3). The signals pass through the conditioning electronics and are then sent to the filter card via ribbon cable 2. The output from the filter card is then sent back to the signal conditioning card via ribbon cable 3, and from there to the analogue-to-digital converter card via ribbon cable 4.

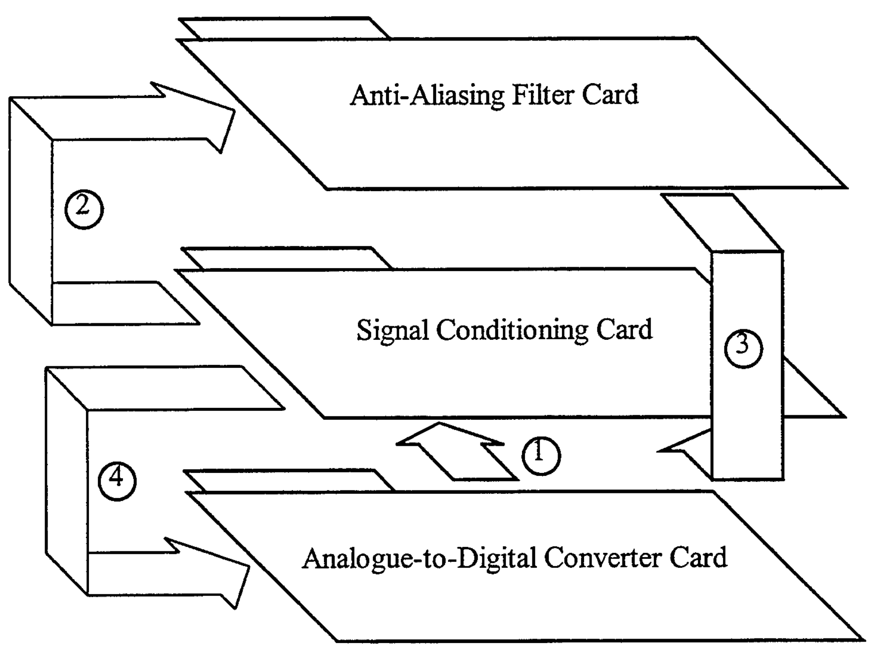


Figure 2. Data Acquisition Cards Schematic

2.2.1 Signal Conditioning Card

The AMRL-designed signal conditioning card has six Integrated Circuit Piezoelectric (ICP) type accelerometer signal channels and two tachometer signal channels. It provides the following functions:

a) a power supply for the accelerometers;

b) signal conditioning for the accelerometer signals;

c) isolation of the high voltage tachometer signals; and

d) signal routing.

A circuit diagram of the card can be found in AMRL Drawing 65971-A1.

2.2.1.1 Accelerometer Power Supply

ICP accelerometers require a constant current power source for operation. This can be between 4 mA and 12 mA depending primarily on the length of cable to the accelerometer. The signal conditioning card provides six 4 mA current sources.

2.2.1.2 Accelerometer Signal Conditioning

The vibration signal from each accelerometer is returned superimposed on the power supply line, allowing two wire operation of the accelerometer. The signal conditioning card extracts this signal from the power supply line and amplifies it. The amplifiers are programmable instrumentation amplifiers with binary gains set by means of a four switch DIP package for each channel. Valid gains are 1, 2, 4, 8 and 16 according to the switch positions shown in Table 1. The DIP switches are accessible to the operator via a cut-out at the card mounting on the left side of the computer.

Table 1. DIP Switch Gains

Gain	SW1	SW2	SW3	SW4
1	OFF	OFF	OFF	X
2	ON	OFF	OFF	X
4	OFF	ON	OFF	X
8	ON	ON	OFF	X
16	X	X	ON	X

Note: X= Don't Care

2.2.1.3 Isolation for the High Voltage Tachometer Signals

Isolation amplifiers are provided on the signal conditioning card to prevent potentially high voltages from destroying the anti-aliasing filter and analog-to-digital conversion circuitry. The 115 VAC 400 Hz main tachometer signal is attenuated to approximately 4 V_{peak} by a resistive divider, and this signal is isolated from the remainder of the circuitry by the isolation amplifier. The tail rotor tachometer signal, which has a much smaller output voltage, is similarly isolated.

2.2.1.4 *Signal Routing*

As commercial off-the-shelf cards are used for both anti-alias filtering and data acquisition, the signal conditioning card provides the appropriate signal routing to each of these cards. This allows straight through ribbon cable connections to be employed between all cards.

2.2.2 Anti-Aliasing Filter Card

The anti-aliasing filter card is a sixteen channel Onsite Instruments Techfilter [Ref 5]. It is a low-pass switched capacitor filter with a programmable cut-off frequency of 1 Hz to 25000 Hz (1 Hz increments up to 250 Hz, 10 Hz increments between 250 Hz and 2500 Hz, and 100 Hz increments above 2500 Hz). Each channel is individually programmable for single-ended or differential inputs; AC or DC coupling; gains of 1, 10, 100 and 1000; and filter or bypass modes. The input and output ranges are ± 5 V, although experimentation has shown mild distortion above ±4.5 V.

2.2.3 Analogue-to-Digital Converter Card

The analogue-to-digital converter card is a Data Translation DT2821-G-8DI [Ref 6]. This card has eight differential analogue inputs that are multiplexed into a single programmable gain amplifier, which has gains of 1, 2, 4 and 8. The output of this amplifier is sampled by a 12 bit analogue-to-digital converter (ADC). The maximum ADC input range is ± 10 V at a gain of 1, but an alternative input range of ± 5 V has been selected by a jumper on the card to match the anti-aliasing filter output. The card has dual channel direct memory access (DMA) with a maximum gap-free throughput of 250 kHz. There are also two digital-to-analogue converters, and sixteen lines of digital input/output that are not used in this application.

2.3 Connector Interface

The connector interface, shown in Figure 3, is an aluminium box fitted into the expansion card recess on the right hand side of the computer. It is held in place by two clips on either side of the box which fit through the recess and bear against the inside of the computer housing. There are four multi-pin connectors mounted in the interface, which are listed in Table 2. In addition, there is a 5 Amp circuit breaker connected into the 28 VDC power line, and a 3 Amp circuit breaker connected into the 115 VAC tachometer line. Details of the pin connections can be found in AMRL Drawing number 66537-A1.

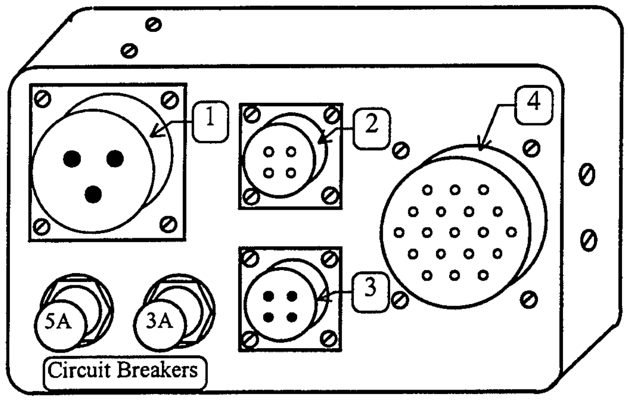


Figure 3. Connector Interface

Table 2. Interface Connectors

#	Connector	Type	Pins
1	28 VDC (power)	ABB 10SL 3PSN	3
2	Tail rotor photocell tacho	MS3112E8-4S	4
3	115 VAC (main rotor tacho)	KPT00A8-4P	4
4	Accelerometers	KPT00A 14-19S	19

2.4 Accelerometers

Endevco Isotron 6259M6-10 accelerometers have been selected for this application, although the system is capable of taking inputs from any standard ICP accelerometer. The 6259M6-10 is a small, wide bandwidth, hermetically sealed accelerometer that is used in a number of helicopter Health and Usage Monitoring System (HUMS) applications. It has a central mounting screw allowing 360° orientation and uses a crystal element operating in annular shear mode. It is case grounded, with the sensing element electrically isolated from the case, and has a large three-pin screw connector with lock-wire holes [Ref 7].

2.5 Tail Rotor Photocell and Photocell Processor

A tachometer signal is obtained from the tail rotor using a Chadwick-Helmuth photocell (P/N 10200) and photocell processor (P/N 10170) [Ref 8], both of which are part of the 8500C rotor track and balance kit. Normally the units are powered by the 8500C balancer, but for this application they receive 28 VDC power through the computer connector interface as shown in AMRL Drawing 66537-A1. The units generate a 10 V_{peak} pulse once-per-revolution of the tail rotor (~20 Hz) that is input to the signal conditioning card.

2.6 Cable Connections

2.6.1 Aircraft Power

The computer is connected to the 28 VDC and 115 VAC aircraft power supplies through two separate cables. The 28 VDC supply provides power for the computer and the rest of the system. The 115 VAC supply provides a convenient main rotor gearbox tachometer signal. This can be done since the 115 VAC generators are directly geared to the gearbox, and the supply frequency is directly proportional to the gearbox shaft speeds.

2.6.2 Transducer Signals

The individual accelerometer and photocell cables all terminate at a single multi-pin connector located in the cabin roof. From there, a split-cable is used to route the accelerometer signals directly to the computer, and the photocell signals to the computer via the photocell processor. Details of the accelerometer and photocell cable installation can be found in Section 3.4.

3. Aircraft Installation

The Black Hawk installation was developed in conjunction with ARDU under ARDU Task 0215. As indicated in Figure 1, the installation is split into two sections: the permanently mounted accelerometers and cabling, and the carry-on/off computer and photocell processor. The tail rotor photocell, while shown as part of the permanent installation in Figure 1, is removable, and can be replaced with a blank panel as described below. This was done because the photocell was borrowed from the rotor track and balance kit and needed to be available for use on other aircraft.

Two Non-Standard Modification (NSM) Orders were drawn up for the installation:

a) NSM Black Hawk 34, Transmission Vibration Analysis Accelerometer Mounting and Cabling Installation.

b) NSM Black Hawk 35, Transmission Vibration Analysis Computer and Cabling Installation.

NSM Black Hawk 34 details the installation of the accelerometers, brackets, and cabling, and the blank photocell panel. NSM Black Hawk 35 details installation of the computer, photocell processor, and photocell.

3.1 Computer Installation

The computer installation is shown in Figure 4. A fabric harness, designed and manufactured by ARDU, contains both the Fieldworks computer and the Chadwick-Helmuth photocell processor (ARDU Drawing KB14G0708). The computer is fastened

inside the harness with Velcro tape and a cord passing through eyelets around the periphery of the harness. The eyelets and cord are also used to secure the harness to a regular aircraft seat, which has been positioned for this purpose directly behind the loadmaster seat on the right side of the aircraft, facing outwards. A flap on the top of the harness allows the computer display panel to be opened, thereby gaining access to the keyboard, and allowing operation of the system in flight. The photocell processor is fastened to the top-rear of the harness behind the display panel flap.

3.2 Accelerometer Locations

Three accelerometers are mounted on the main rotor gearbox, one on the intermediate gearbox, and one on the tail rotor gearbox. Two different types of mounting brackets are used: one for the main rotor gearbox (AMRL Drawing 66565-A2), and one for the intermediate and tail rotor gearboxes (AMRL Drawing 66566-A2). All brackets are fastened under the existing gearbox flange nuts, all accelerometers are lock-wired to their brackets, and all accelerometer cable connectors are lock-wired to their accelerometers.

3.2.1 Main Rotor Gearbox

One accelerometer is mounted on each input module, as shown in Figure 5. The upper photograph has been taken from a viewpoint forward and above the main rotor gearbox looking rearwards along the centre-line of the helicopter. The input modules are partially visible at the sides of the photograph, with the front of the main module visible in the centre.

The third accelerometer is mounted on the left-rear of the main module sump, as shown in Figure 6.

3.2.2 Intermediate Gearbox

One accelerometer is mounted at approximately 4 o'clock (looking forward) on the output housing flange of the intermediate gearbox, with its sensitive axis in the radial direction, as shown in Figure 7.

3.2.3 Tail Rotor Gearbox

One accelerometer is mounted at approximately 9 o'clock on the output housing flange of the tail rotor gearbox, with its sensitive axis in the radial direction, as shown in Figure 8. The viewpoint is above and to the rear of the gearbox looking forward and down.

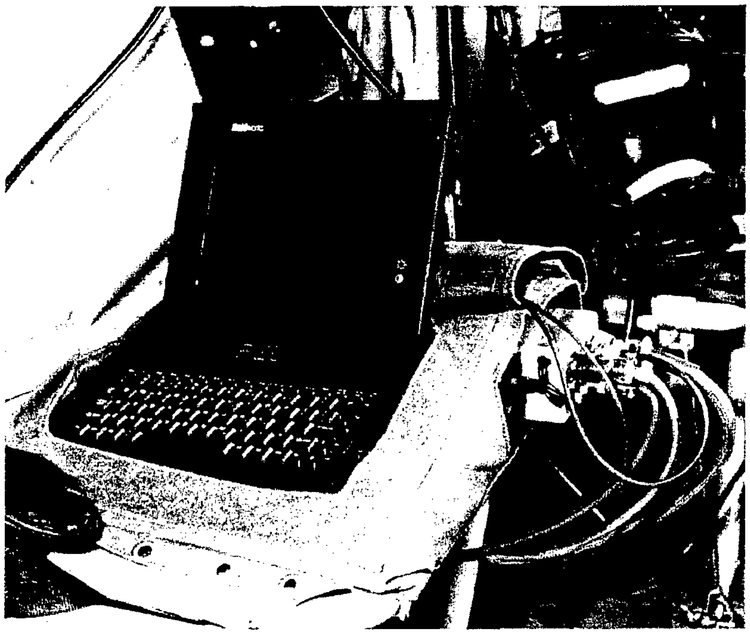


Figure 4. Computer Installation

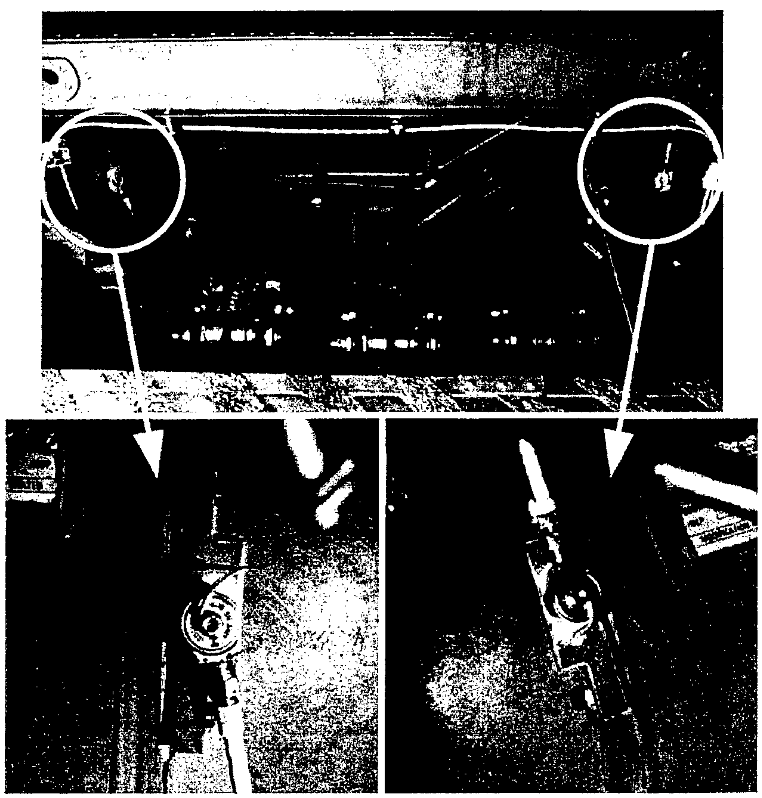


Figure 5. Left and Right Input Module Accelerometers

3.3 Photocell Location

The photocell is mounted on top of the tail pylon approximately 480 mm behind the centre-line of the tail rotor hub, and points down at the rotor disc with a 15° angle to the horizontal to reduce interference from direct sunlight. The beam length is approximately 275 mm to the rotor blade target, which is a piece of reflective tape, approximately 20 × 50 mm, affixed to the inside edge of one rotor blade.

The mounting bracket was designed by ARDU. It fits over a standard access panel on top of the pylon, and is secured with two camloc fasteners. A blank panel with a dummy connector has been made to cover the opening and allow positive retention of the cable plug when the photocell is not needed. A diagram of the mount is shown in Figure 9, and details can be found in ARDU Drawing KB14B0719.

3.4 Transducer Cables

All the permanently mounted accelerometer and photocell cabling is installed along the most direct routes from the transducers to a single multi-pin connector in the cabin roof. The multi-pin connector has been fitted to an empty connector cut-out in a panel in the forward end of the main cabin roof just to the left of the centre-line (approximate position STA 295, BL 10 Left, WL 270), as shown in Figure 10.

Endevco EW961 shielded twisted pair cable is used for all the accelerometer cables. The accelerometer signals are passed along the twisted pair, and the shield is grounded to the gearbox through the connector shell and the accelerometer casing. The shields are not grounded at the computer connector interface to avoid interference from ground loops.

Two shielded twisted pair cables are used for the Chadwick-Helmuth photocell in place of the four-conductor cable used for the rotor track and balance application. One twisted pair carries power and a 100 kHz drive signal to the photocell, and the other twisted pair carries the return signal. The shields are connected to the connector shells at both ends.

The intermediate and tail gearbox accelerometer cables, and the photocell cables pass through the tail-boom fold connector panel via detachable connections. The connector panel was modified by ARDU to incorporate them. Details can be found in ARDU Drawing KB14V0072.

Further information on the cabling and connectors can be found in AMRL Drawing 66537-A1 and ARDU Drawing KB14Z0707.

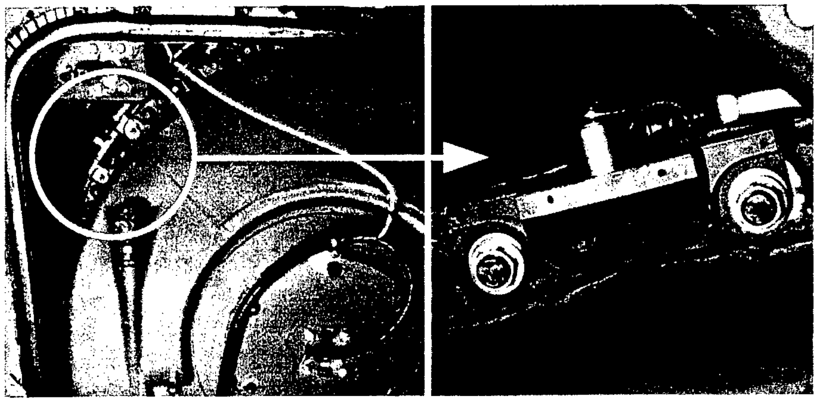


Figure 6. Main Module Accelerometer

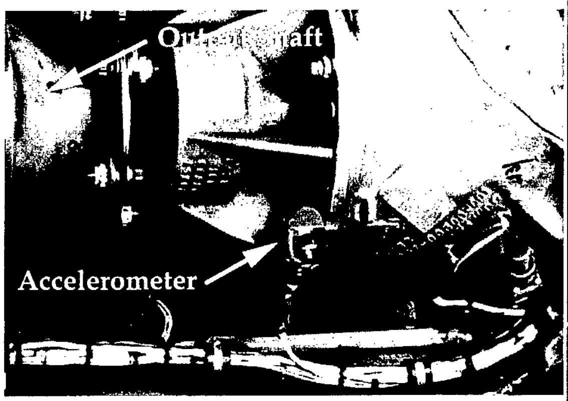


Figure 7. Intermediate Gearbox Accelerometer

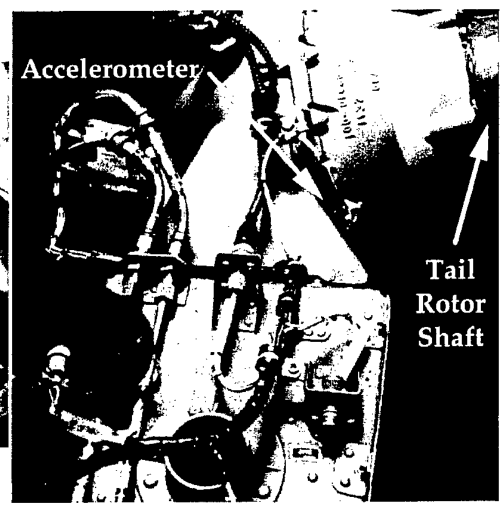


Figure 8. Tail Gearbox Accelerometer

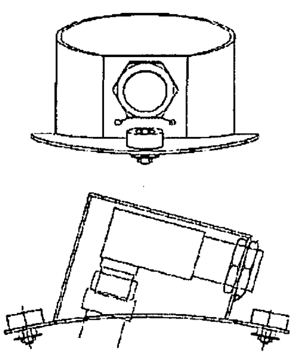


Figure 9. Photocell Bracket (with photocell)

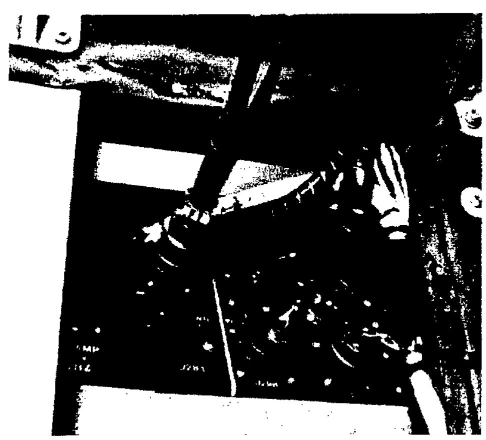


Figure 10. Multi-pin Cabin Connector

4. System Operation

4.1 Frequency of Use

The vibration monitoring system should be used at regular intervals. Suggested intervals range between 10 to 50 aircraft hours. The selection of an interval involves a compromise between the effort required of maintenance crews and the chance on an incipient fault progressing through to catastrophic failure before detection. As there is limited data available on which to base a decision at this stage, an interval for the Black Hawk helicopter has not been chosen. One strategy may be to start with a relatively short interval, which could be lengthened as data and experience are accumulated.

4.2 Operating Procedure

The vibration monitoring system is operated using the following procedure:

1. The computer and other carry-on equipment are installed in the aircraft.
2. A data acquisition program is executed during the next flight. This acquires vibration data from each gearbox plus tachometer data from one of the tachometer signals and stores it in raw data files on the hard disk.
3. The computer and other carry-on equipment are removed from the aircraft.
4. A data processing program is executed. This computes a synchronous vibration signal average for every gearbox shaft from the raw data files. Each signal average represents the vibration signature of that shaft and the gears on that shaft.
5. A data analysis program is executed to analyse the signal averages. This program calculates a number of condition indices from each signal average. These indices measure various characteristics of the signal average, and are sensitive to different types of faults [Ref 9].

An overview of the database and system software which performs this procedure is provided in Appendix 1. The database uses the aircraft tail numbers, gearbox serial numbers, and gearbox time since new (TSN) to keep track of the vibration data acquired and processed by the system.

A list of the condition indices currently used by the system is provided in Table 3. They were selected at the time the software written, and may be changed or replaced with improved indices at a future date. Indices 1 to 8 are computed for each shaft, and indices 9 to 15 are computed for each gear on the shaft. Thus for a shaft with two gears, there will be a total of 22 indices. The condition indices for each signal average are stored in a text file for trending purposes. Normally, warning and danger limits would be prescribed for each index, but as a vibration database for the Black Hawk has not yet been accumulated, this feature has been omitted from the software at this stage.

The indices, however, can be manually monitored while the database is being accumulated.

Table 3. Condition Indices

#	Index	Description
1	SIG_RMS	RMS of the signal average.
2	SIG_CF	Crest factor (peak-to-peak/RMS) of the signal average.
3	SIG_K	Kurtosis of the signal average.
4	SIG_1x	Amplitude of the once-per-rev component (balance).
5	SIG_2x	Amplitude of the twice-per-rev component (alignment).
6	RES_RMS	RMS of the residual signal [1] / RMS of the signal average.
7	RES_CF	Peak-to-peak of the residual signal [1] / RMS of the signal average.
8	RES_K	Kurtosis of the residual signal [1].
9	MESH_SUM	Sum of the amplitudes of the gear mesh harmonics.
10	MESH_RATIO	Amplitude of 2 × gear mesh component / 1 × gear mesh component.
11	MESH_MOD1	Sum of 1st order sidebands / sum of gear mesh harmonics.
12	MESH_MOD2	Sum of 2nd order sidebands / sum of gear mesh harmonics.
13	NB_RMS	RMS of the narrow band envelope [2] / centre frequency amplitude.
14	NB_CF	Peak of the narrow band envelope [2] / centre frequency amplitude.
15	NB_K	Kurtosis of the narrow band envelope [2].

1 The residual signal is obtained by removing the gear mesh and other regular frequencies from the signal average.

2 The narrow band envelope is the envelope of the signal obtained by removing all the frequency components outside a narrow band around a gear mesh frequency, and removing the gear mesh frequency, from the signal average.

5. ARDU Flight Trial

A flight trial of the transmission vibration monitoring system was carried out by the RAAF Aircraft Research and Development Unit during the period 18 to 20 October 1995 at RAAF Base Edinburgh.

The objectives of this flight trial were:

a) to test the vibration monitoring system for interference and operational problems in an airborne helicopter; and

b) to acquire vibration data under various flight conditions, and determine which are the most suitable for the analysis of each gearbox.

5.1 Aircraft Details

The system was installed in Black Hawk A25-206. The gearbox serial numbers for this aircraft are listed in Table 4. All the gearboxes, except the tail rotor gearbox, have been installed in this aircraft since new. The tail rotor gearbox was previously fitted to A25-105, before it was removed on 16/11/94 for a MOD/STI at 1299.2 hours, then

installed in A25-206 on 15/8/95. The previous tail rotor gearbox (S/N 00601438) in A25-206 was removed due to corrosion.

Table 4. A25-206 Gearbox Details

Gearbox	Serial Number	Hours @ 18/10/95
Left Input Module	26403586	888.1
Right Input Module	26403587	888.1
Main Module	52500049	888.1
Intermediate	00501727	888.1
Tail Rotor	00601156	1300.2

5.2 Electrical Interference Test

The transmission vibration monitoring system was subjected to an electro-magnetic interference (EMI) test in the aircraft prior to the first flight, and was found not to interfere with any aircraft system. It was found, however, that the red and white strobe lights on top of the tail pylon did interfere with the accelerometer and photocell signals from the tail rotor gearbox. Whenever either of the strobes flashed, a corresponding large voltage spike was induced in the signals, rendering them unusable. The cause was traced to the close proximity of the signal cables to the strobe light cables in the tail pylon. Unfortunately this could not be avoided due to the lack of alternative cable routes. The compromise solution arrived at was to switch off the strobe lights during data acquisition.

5.3 In-Flight Operation

No operational problems were encountered with the computer installation. The ambient cabin vibration did not make the computer screen uncomfortable to read, nor cause difficulty in operating the keyboard, although care needed to be exercised during brief bursts of turbulence. The computer screen was also bright enough to be easily viewed when the outside light levels were high (less than 10% cloud).

5.4 Vibration Data Acquired

Four flights were undertaken during the trial. Data collected from the first three flights were used to debug and adjust the system set-up (details of the system set-up can be found in Appendix 2). A pre-flight summary for the fourth flight can be found in Table 5. Table 6 lists the gearbox hours before the start of this flight.

Table 5. Pre-Flight Summary

Aircraft:	A25_206	Location:	Edinburgh
Start Fuel:	2180 lb	All Up Weight:	16600 lb
Stores:	Two empty 230 gal external fuel tanks on outboard ESSS pylons		
ATIS:	QNH 1026, OAT 10°C, Wind 140°/170° 8-15 knots		

Table 6. Gearbox Hours

Gearbox	Hours
Left Input Module	891
Right Input Module	891
Main Module	891
Intermediate Gearbox	891
Tail Gearbox	1303

5.4.1 Flight Conditions Flown

The flight conditions flown are listed in Table 7. They were chosen to examine the effects on the gearbox vibration of:

a) engine torque, which is the most important factor affecting the input and main module gearbox vibration;

b) banked turns, which were included to discover whether turning the helicopter, as may be necessary for a number of reasons (eg if an airspace boundary is approached), could be tolerated during data acquisition; and

c) tail rotor torque, which is the most important factor affecting the intermediate and tail rotor gearboxes. However, as tail rotor torque is less easy to quantify and control, it was only varied through simple tail rotor turns.

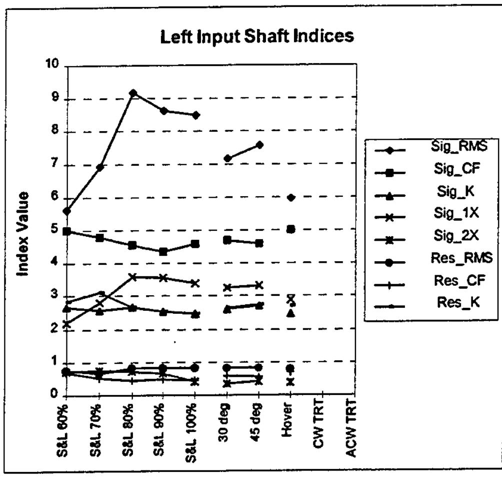
Table 7. Flight Conditions

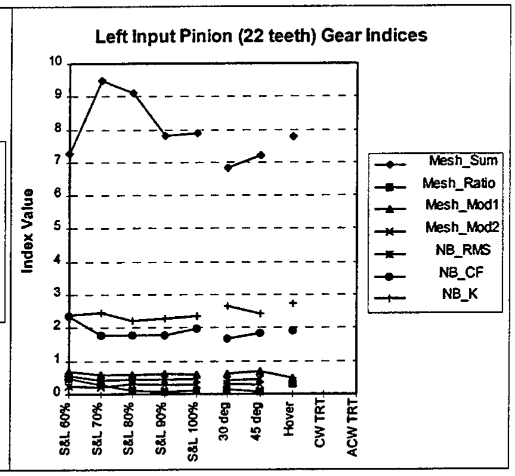
#	Flight Condition	Altitude(ft)	KIAS	Torque(%/%)	NR
1	Straight and level flight - 60% torque	1300	100-110	60/60	100
2	Straight and level flight - 70% torque	1300	115-120	70/70	100
3	Straight and level flight - 80% torque	1100	125	80/80	100
4	Straight and level flight - 90% torque	1100	135	90/90	100
5	Straight and level flight - 100% torque	1100	140	100/100	100
6	Right turn 30° constant altitude	1300	120	80/80	100
7	Right turn 45° constant altitude	1300	120	80/80	100
8	Hover	25	0	60/60	100
9	Clockwise tail rotor turn (~11sec/360°)	25	0	60/60	100
10	Anti-clockwise tail rotor turn (~16sec/360°)	25	0	60/60	100

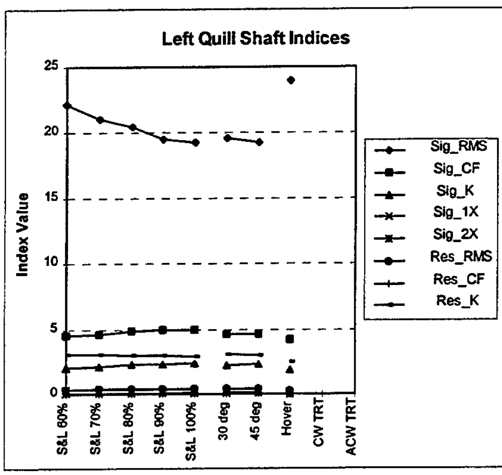
5.5 Results of Vibration Data Analysis

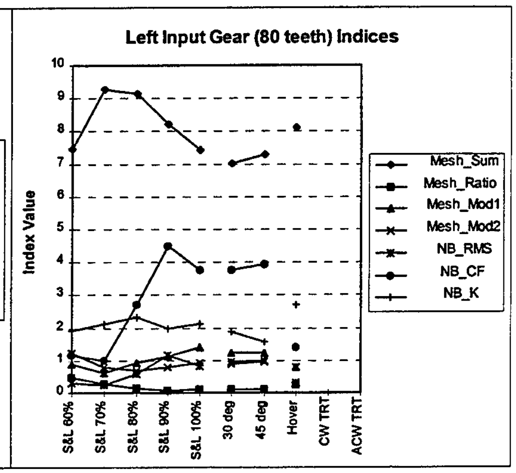
The results of the data analysis are presented below. The condition indices for each shaft and gear have been extracted from their trend files, inserted into an Excel spreadsheet, and plotted for each flight condition. The plot lines have been broken into the three sections representing the changes in engine torque, turn bank angle, and tail rotor torque. Due to the large amount of data, all the indices for each shaft or gear have been compiled on one plot. Unfortunately, this obscures some of the smaller valued indices, but the intention is to give an overview of the results rather than a detailed presentation.

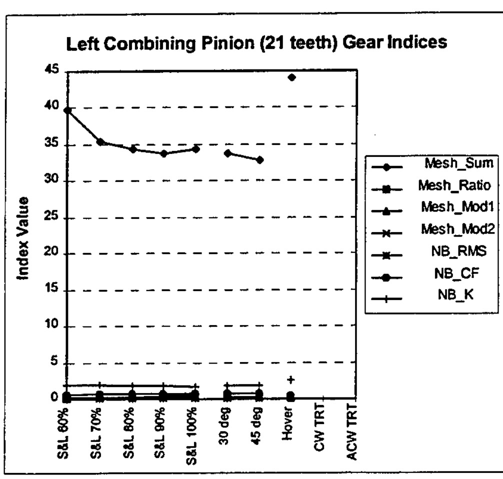
5.5.1 Left Input Module

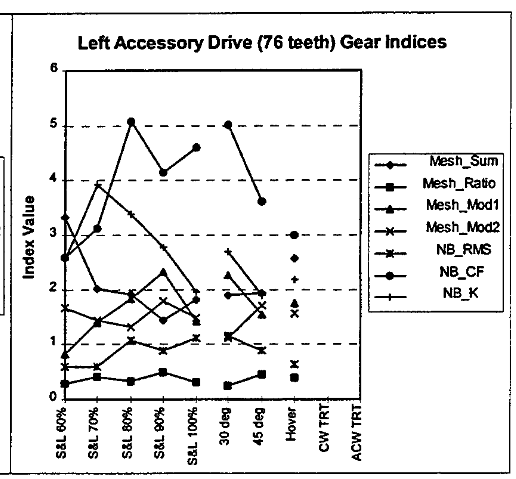




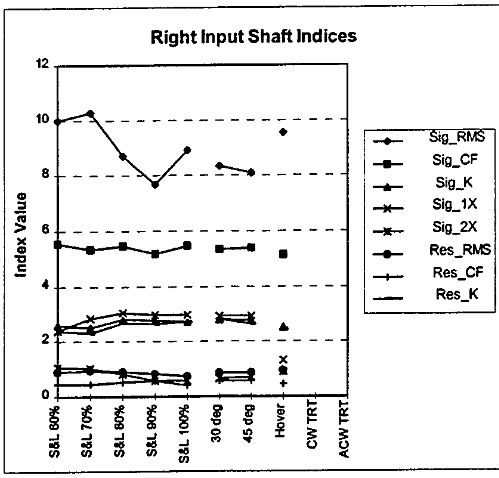


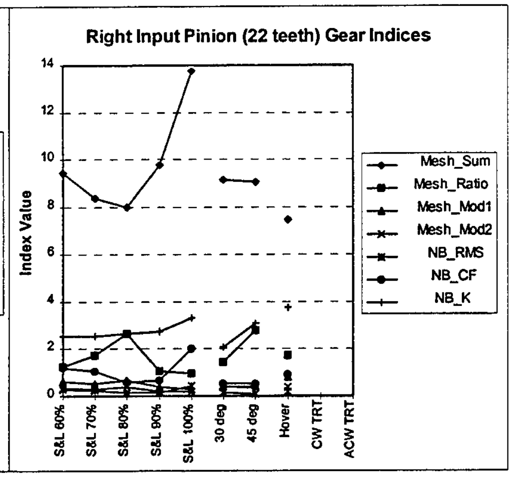


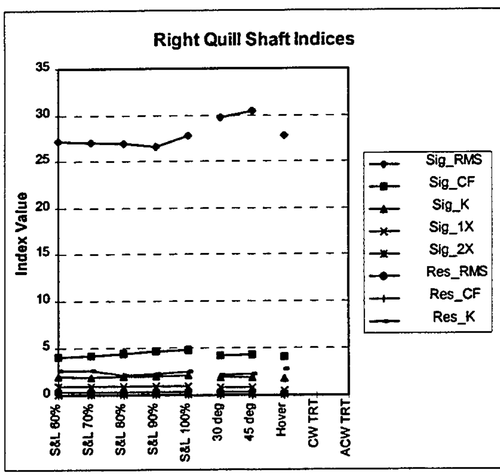


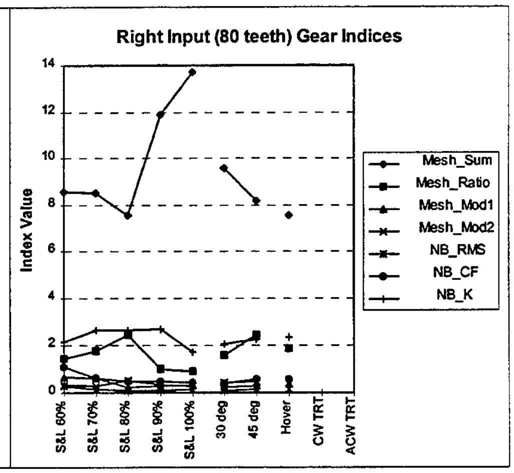


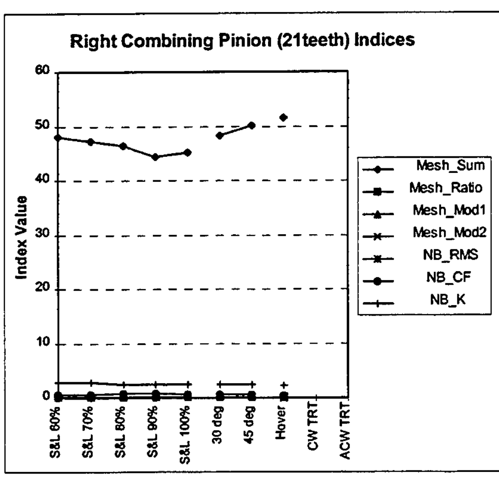
5.5.2 Right Input Module

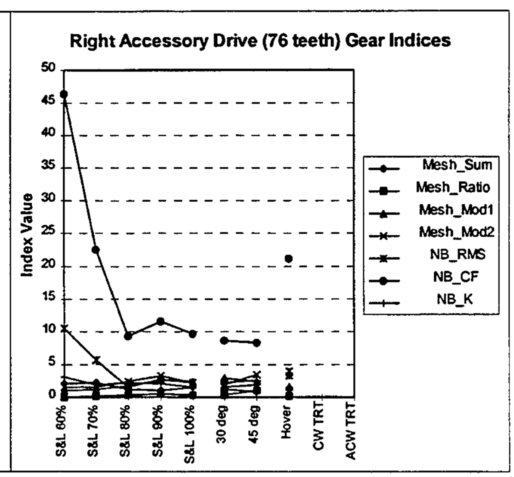




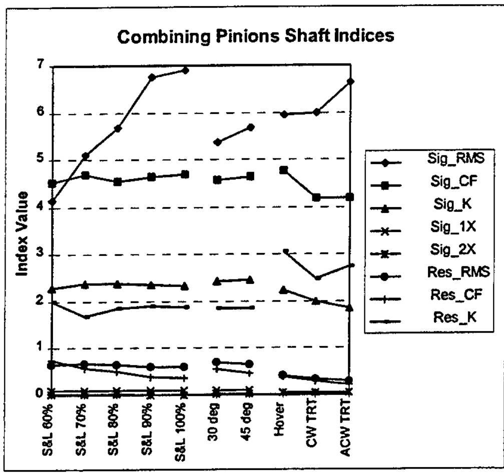


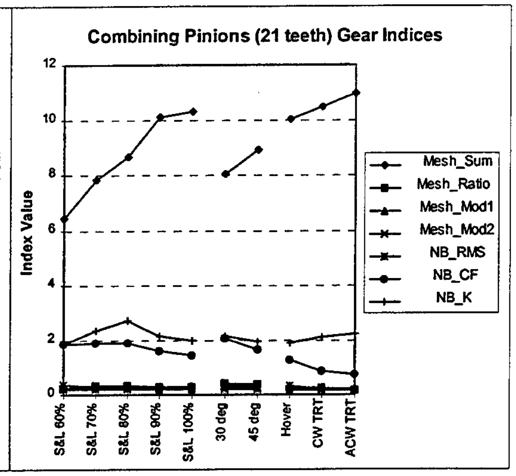


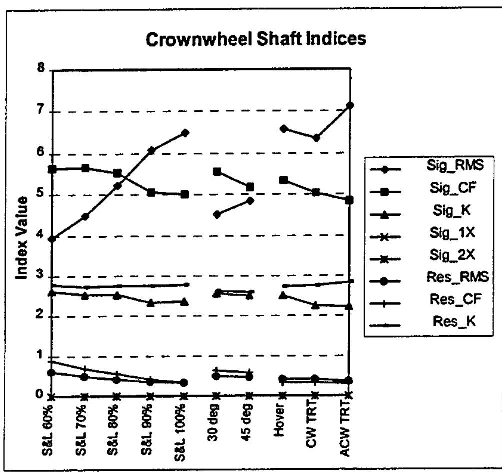


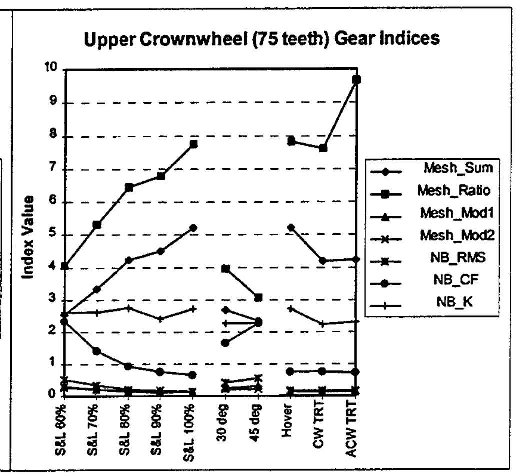


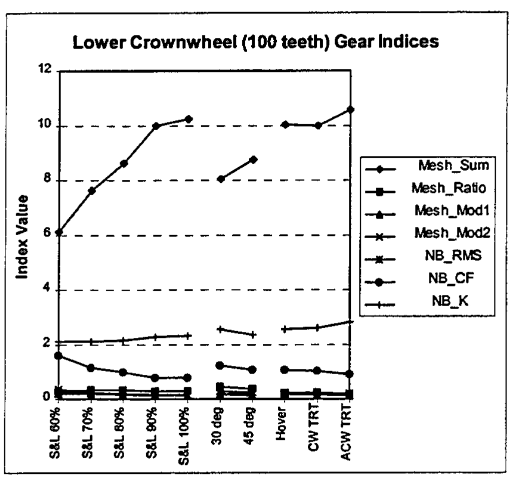
5.5.3 Main Module

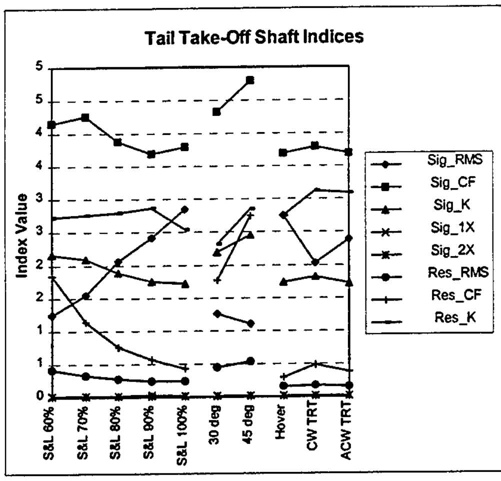


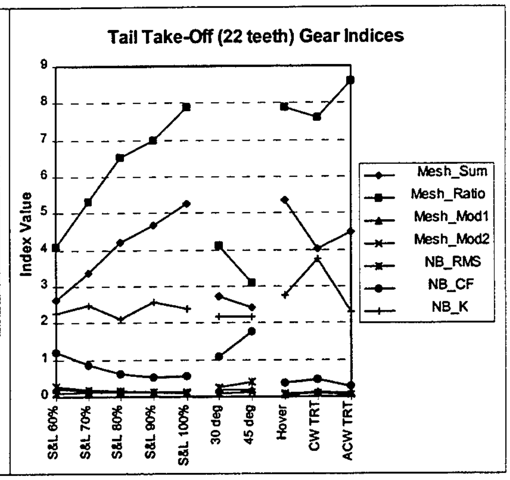









Tail Take-Off Shaft Indices
Index Value
Sig_RMS
Sig_CF
Sig_K
Sig_1X
Sig_2X
Res_RMS
Res_CF
Res_K
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT


Tail Take-Off (22 teeth) Gear Indices
Index Value
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K
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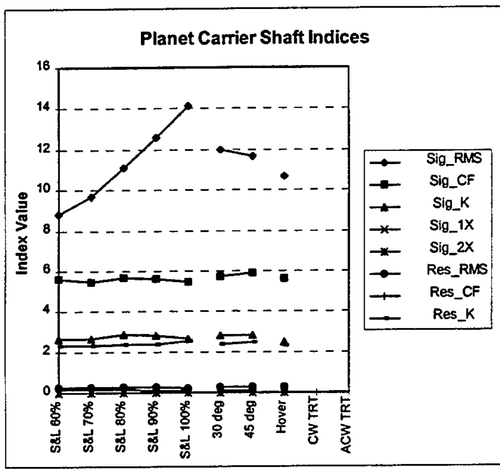
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT


Planet Carrier Shaft Indices
Index Value
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Sig_CF
Sig_K
Sig_1X
Sig_2X
Res_RMS
Res_CF
Res_K
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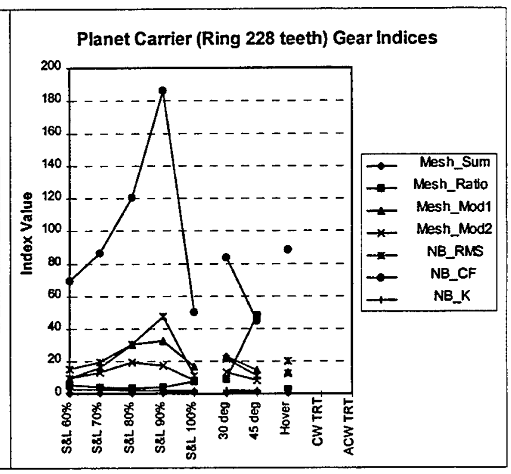
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT


Planet Carrier (Ring 228 teeth) Gear Indices
Index Value
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K
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S&L 90%
S&L 100%
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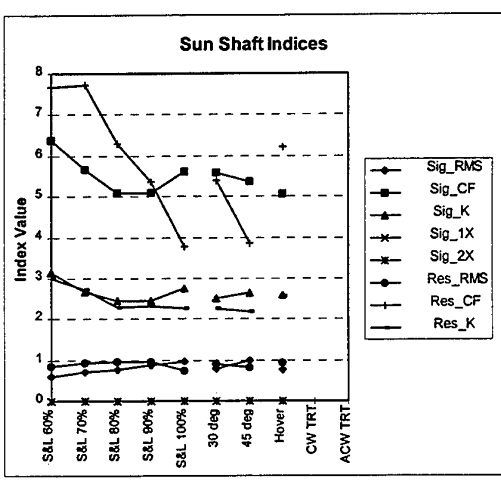
45 deg
Hover
CW TRT
ACW TRT


Sun Shaft Indices
Index Value
Sig_RMS
Sig_CF
Sig_K
Sig_1X
Sig_2X
Res_RMS
Res_CF
Res_K
S&L 60%
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S&L 80%
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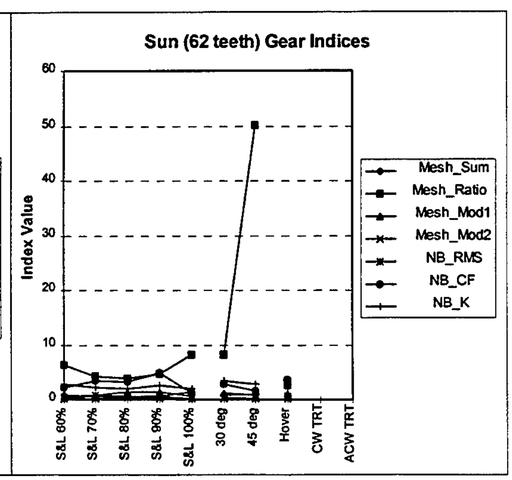
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT


Sun (62 teeth) Gear Indices
Index Value
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K
S&L 60%
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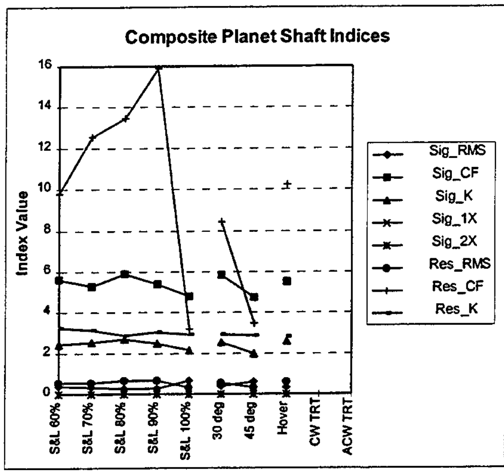
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT


Composite Planet Shaft Indices
Index Value
16
14
12
10
8
6
4
2
0
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
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Sig_RMS
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Sig_K
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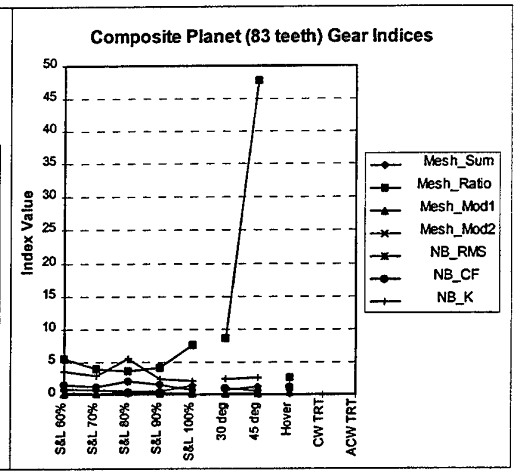
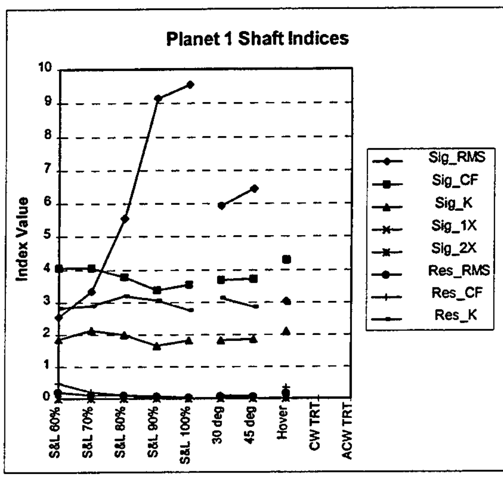
Res_RMS
Res_CF
Res_K


Composite Planet (83 teeth) Gear Indices
Index Value
50
45
40
35
30
25
20
15
10
5
0
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K


Planet 1 Shaft Indices
Index Value
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9
8
7
6
5
4
3
2
1
0
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
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Sig_K
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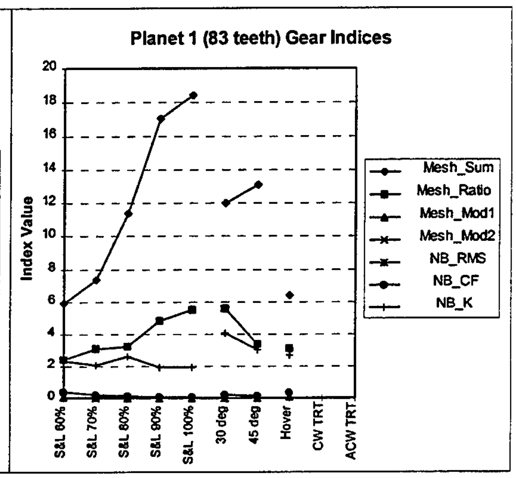
Res_RMS
Res_CF
Res_K


Planet 1 (83 teeth) Gear Indices
Index Value
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18
16
14
12
10
8
6
4
2
0
S&L 60%
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S&L 80%
S&L 90%
S&L 100%
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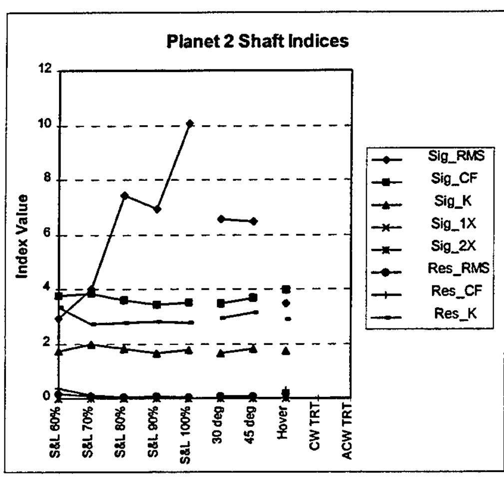
NB_RMS
NB_CF
NB_K


Planet 2 Shaft Indices
Index Value
12
10
8
6
4
2
0
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
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Sig_K
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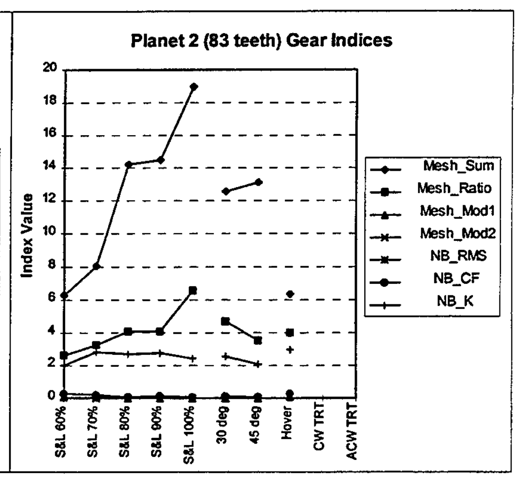
Sig_2X
Res_RMS
Res_CF
Res_K


Planet 2 (83 teeth) Gear Indices
Index Value
20
18
16
14
12
10
8
6
4
2
0
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
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CW TRT
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Mesh_Ratio
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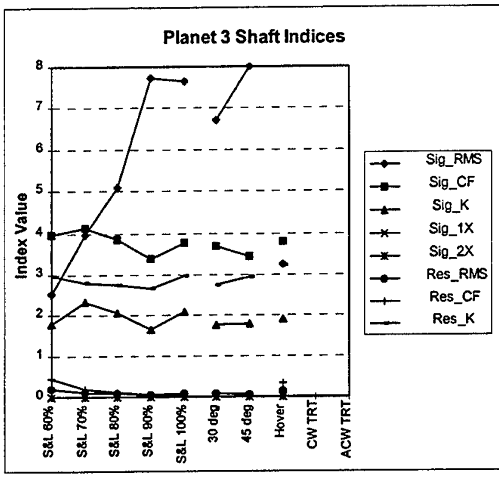
NB_RMS
NB_CF
NB_K


Planet 3 Shaft Indices
Index Value
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
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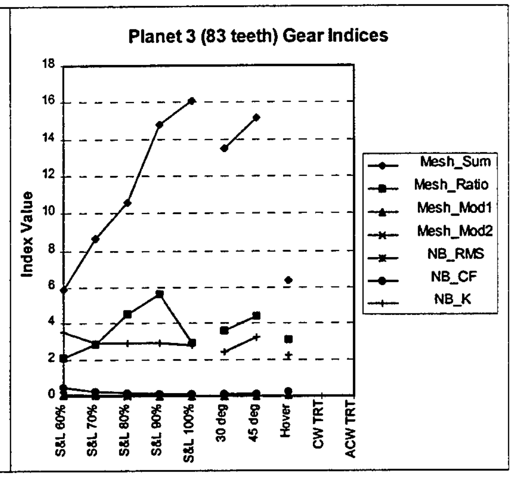
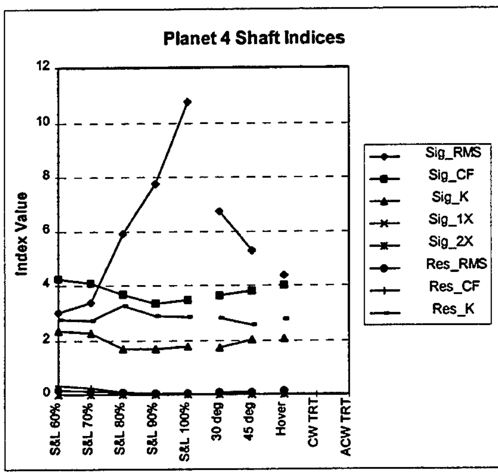
Res_RMS
Res_CF
Res_K


Planet 3 (83 teeth) Gear Indices
Index Value
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K


Planet 4 Shaft Indices
Index Value
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S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
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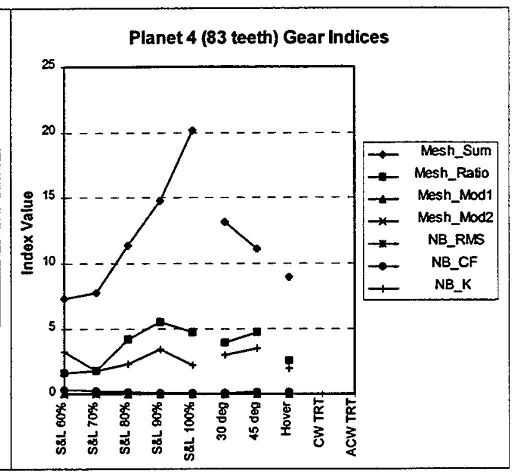
Res_RMS
Res_CF
Res_K


Planet 4 (83 teeth) Gear Indices
Index Value
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
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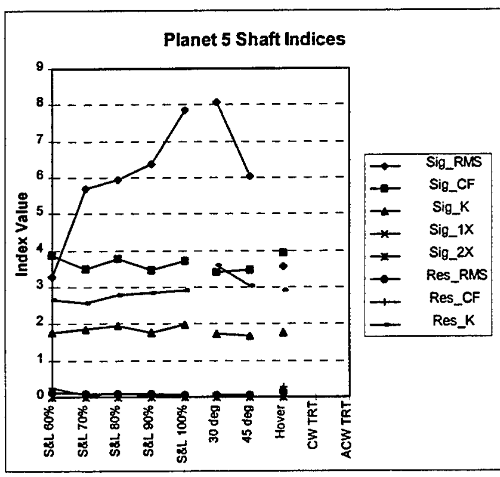
ACW TRT
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K


Planet 5 Shaft Indices
Index Value
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
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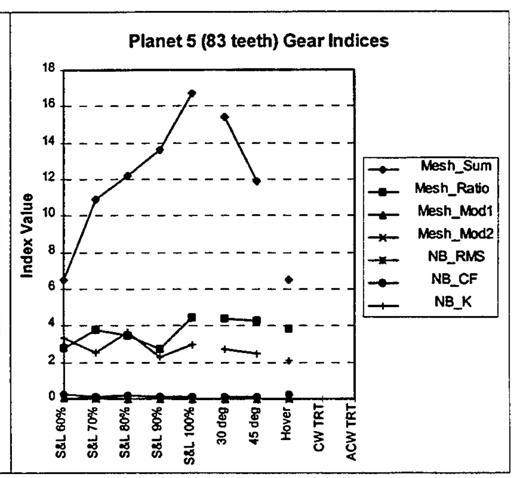
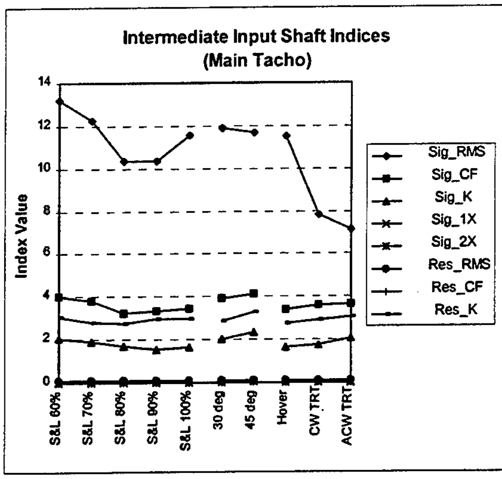
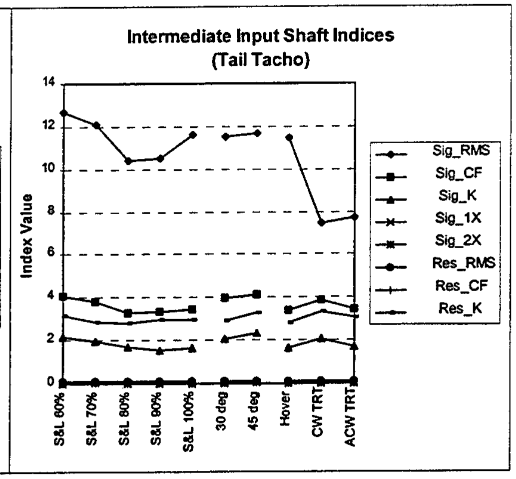
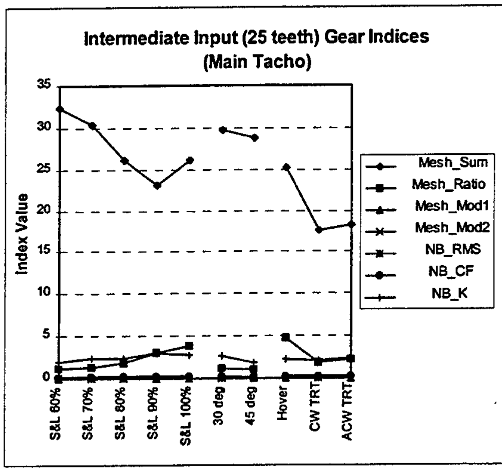
Res_RMS
Res_CF
Res_K

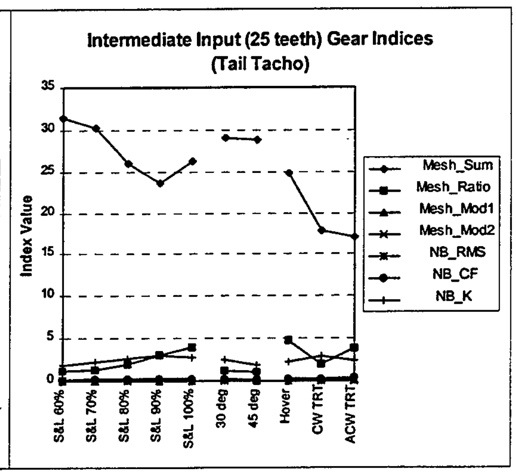

Planet 5 (83 teeth) Gear Indices
Index Value
S&L 60%
S&L 70%
S&L 80%
S&L 90%
S&L 100%
30 deg
45 deg
Hover
CW TRT
ACW TRT
Mesh_Sum
Mesh_Ratio
Mesh_Mod1
Mesh_Mod2
NB_RMS
NB_CF
NB_K

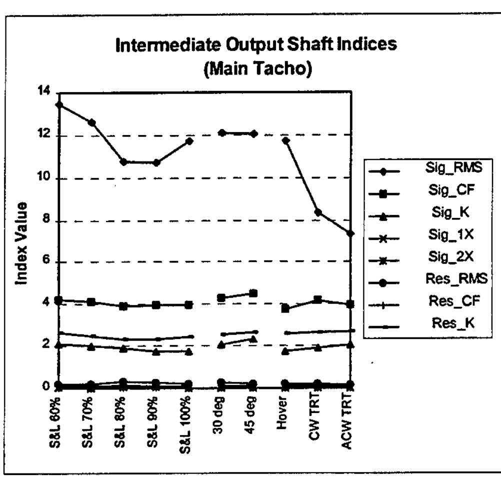
5.5.4 Intermediate Gearbox

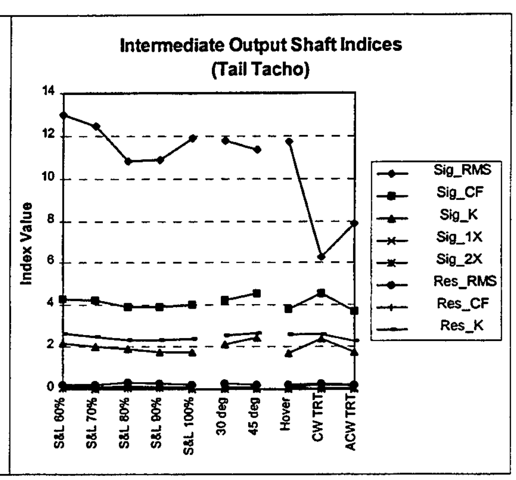


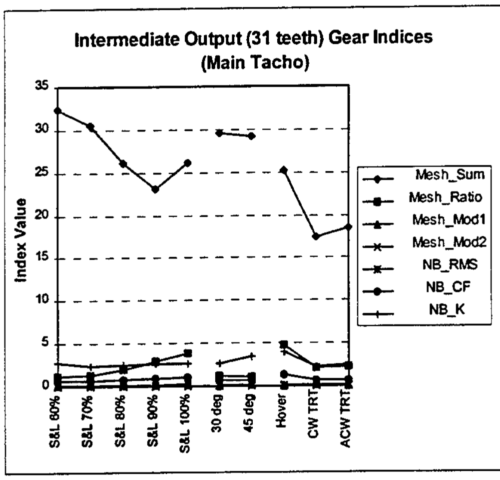


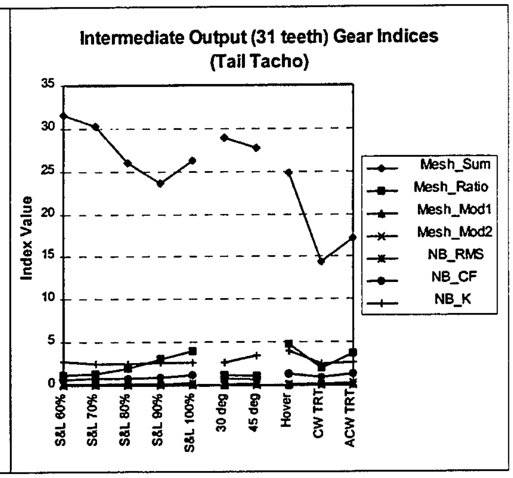




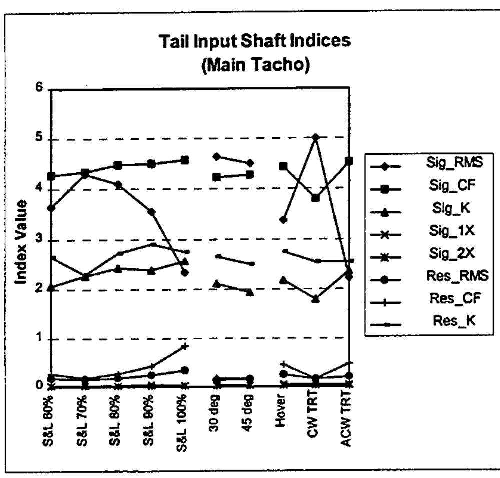


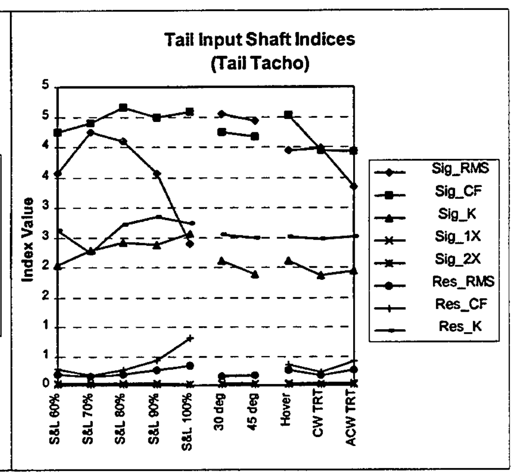


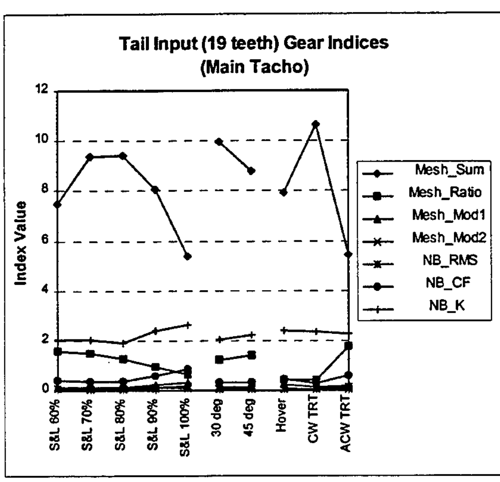


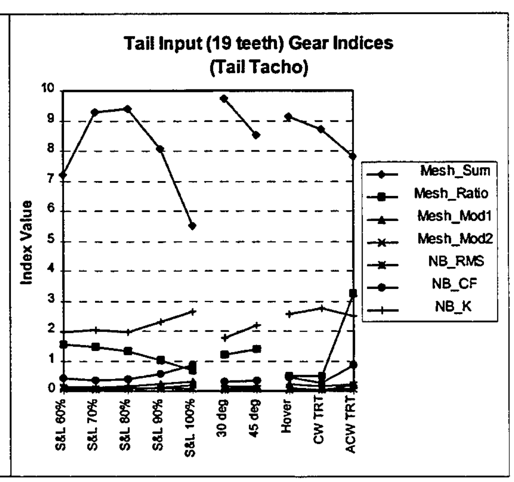


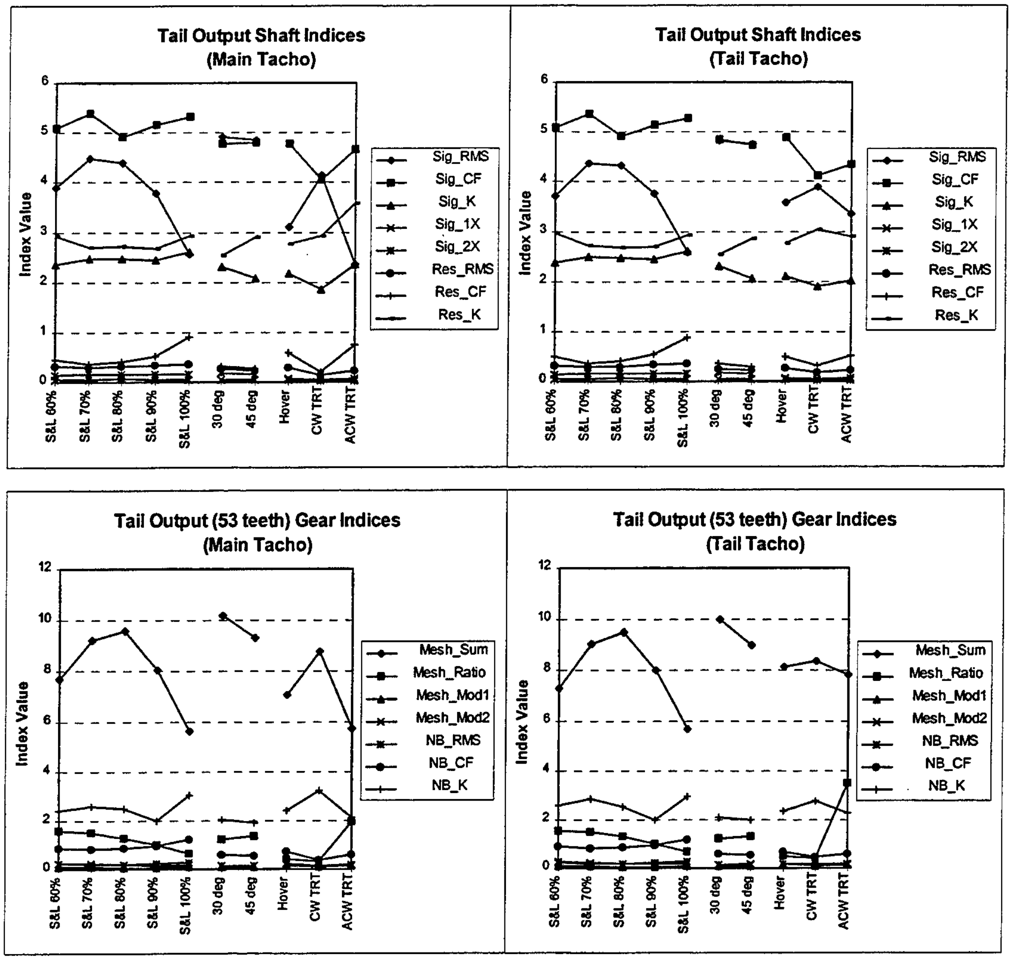
5.5.5 Tail Rotor Gearbox











5.6 Discussion

The above results, and other effects noted during the analysis of the data, are discussed below.

5.6.1 Flight Condition Effects

It can be seen from Section 5.5 that the effect of the flight conditions on the condition indices varies from one index to another. Some indices are relatively unaffected, while others show considerable variation. Also, those indices that show a large variation for one shaft or gear, do not necessarily show a similar variation for another shaft or gear. For example, Sig_RMS exhibits different variations for the left and right input shafts.

The reasons for this complex behaviour are difficult to ascertain. Unfortunately, the statistical variation of the results cannot be determined because of a lack of useable data from the previous flights (due to incorrect filter settings). The results do strongly suggest, however, that:

a) engine torque does have a strong effect on the input and main module gearbox vibration;

b) banked turns do have an appreciable effect on the gearbox vibration, and should therefore be avoided, or the bank angle kept as shallow as possible, during normal data acquisition; and

c) tail rotor torque also has a strong effect on the intermediate and tail rotor gearbox vibration, and variations in this torque should be minimised during normal data acquisition.

It is also clear from the results that, for index trending purposes, the vibration data for each gearbox should always be acquired under the same flight conditions.

5.6.2 Planet Gear Modulation Effects

It should be noted that the signal averages of the planet carrier are affected by a naturally occurring modulation brought about by the planets passing the accelerometer on the ring gear. This is evident by the 'humps' in the signal average, an example of which is shown in Figure 11. As there are five planets, the modulation manifests itself in the frequency domain by enhancing every fifth shaft order. This distorts the relative amplitudes of the gear mesh frequency, its harmonics, and sidebands. Any condition indices which are calculated from these components should therefore be ignored.

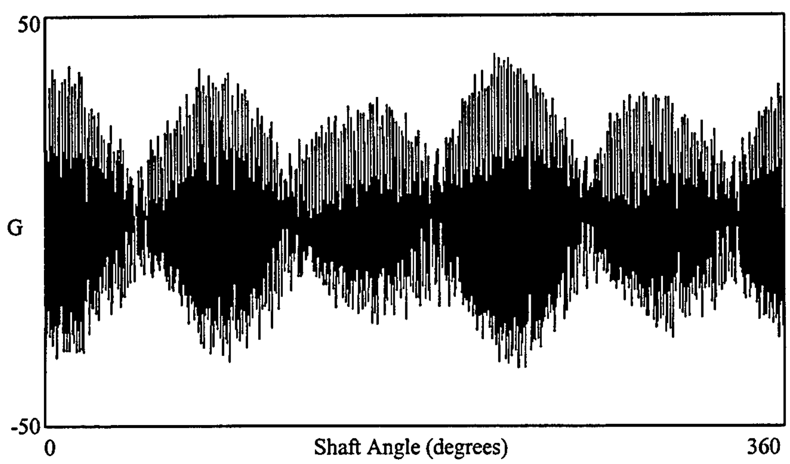


Figure 11. Planet Carrier Signal Average

5.6.3 Extraneous Tail Rotor Gearbox Vibration

The tail rotor gearbox vibration data was found to contain large impulses in all the forward flight conditions. As these impulses were not evident in the hover flight conditions, and could not be expected to form part of the normal gearbox vibration, they would appear to come from an extraneous source.

A typical sample of this data is shown in Figure 12, with a close-up view of a typical impulse shown in Figure 13. The impulses are quasi-regular, and exhibit the characteristics of impacts (ie exponentially damped sinusoid). The impulse repetition rate varies, with some tens of impulses occurring quite regularly at one rate, followed by intermittent impulses, followed by another series of impulses at a slightly different rate. The repetition rates approximately correspond with multiples of the tail rotor frequency. The variation in rates, however, suggests a non-synchronous, possibly aerodynamic, cause. The impulses also vary in magnitude, sometimes disappearing into the general background vibration for short periods.

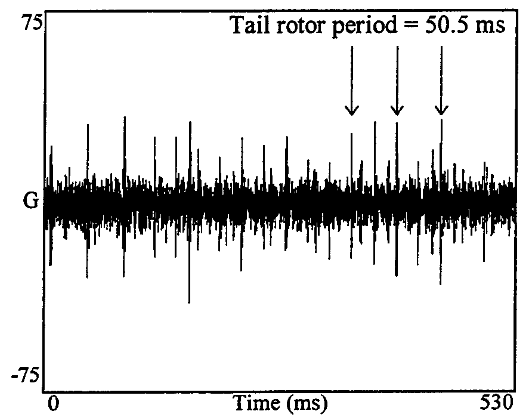


Figure 12. Typical Tail Accelerometer Signal During Forward Flight

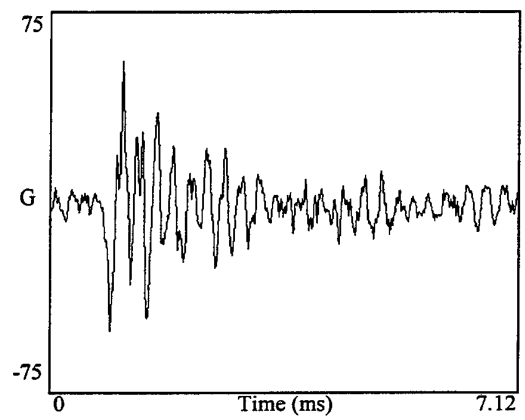


Figure 13. Typical Impulse

It is speculated that the cause of the impulses is one or more of the following, in decreasing order of probability:

a) The main rotor wake is interacting with the tail rotor. That is, during forward flight the main rotor wake is swept backwards and intersects the tail rotor disc area. When a main rotor blade tip vortex encounters a tail rotor blade, it creates an effect not unlike that of an impact on the tail rotor blade, and this is then transferred down the blade to the gearbox and the accelerometer. Due to the differing relative positions of the main and tail rotor blades (Tail Rotor $\approx 4.61 \times$ Main Rotor), and the inherent aerodynamic flow variations, the tip vortices intersect with the tail rotor blades at varying locations in the disc, and with varying strength, causing the different impact repetition rates and magnitudes.

b) The main or tail rotor wake is interacting with the tail pylon and/or stabilator. That is, when the blade tip vortices hit the tail pylon or stabilator they cause an impulse which is transferred through the structure to the accelerometer. If the tail rotor wake was a strong contributing factor, however, it would be expected that this effect would be present during hover as well as forward flight. Also, if the impulses were originating in the stabilator, they would be expected to be visible in the intermediate gearbox accelerometer signal, which they are not.

c) Other aerodynamic features of forward flight are interacting with the tail pylon and/or stabilator. This is not expected to be significant as the main and tail rotor wakes will be the dominant aerodynamic features.

Whatever the cause of the impulses is, they remain undesirable and, without further flight trials to determine if they disappear at lower forward velocities, the vibration data for this gearbox should only be acquired during hover.

5.6.4 Tail Rotor Tachometer Signal

It was unclear before the flight trial whether a tachometer signal from the tail rotor would be required. Synchronous signal averaging requires a highly accurate speed reference signal, and the long tail drive shaft has the potential to introduce a significant amount of phase jitter between the main rotor gearbox tachometer signal and the intermediate and tail rotor gearbox shafts.

The results shown in Sections 5.5.4 and 5.5.5 indicate that there does not appear to be much difference between using the main and tail tachometer signals during forward flight. In these flight conditions the condition indices are closely matched. During hover and tail rotor turns, however, much larger differences between the indices are evident. Examination of the signal averages in these cases reveals some slight differences between the signal averages in both the time and frequency domains and may be evidence of a small amount of phase jitter during these flight conditions.

A possible explanation for these results is that during forward flight the tail rotor torque remains almost constant, but during hover, and particularly during tail rotor turns, the tail rotor pitch, and hence torque, is continuously adjusted by the pilot to maintain the flight condition. This torque variation would then directly contribute to the phase jitter by causing different amounts of twist in the tail drive shaft.

Since vibration data should be acquired from the tail rotor gearbox while hovering, see Section 5.6.3, the tail rotor tachometer signal will be necessary for acquiring data from this gearbox. It will also be highly desirable for acquiring data from the intermediate gearbox.

5.6.5 Selection of Flight Conditions

The selection of the most suitable flight conditions for the analysis of vibration from each gearbox has been based on the following criteria:

a) The flight condition should be easily attainable.

b) The vibration signal should not be corrupted with extraneous signals.

c) The flight condition should place the gearbox under a moderate-to-high torque.

This last criterion is based on the expectation that gearbox faults will, in general, be more easily detected at higher loads because a higher load will increase the severity of the disturbance brought about by the fault. A higher load, for example, will reduce lubricant film thicknesses to give stronger surface interactions, open fatigue cracks more widely, put greater stress on misalignments, etc.

Based on the discussion in the preceding sections, the flight conditions recommended as the most suitable for the analysis of vibration from each gearbox are listed in Table 8. Straight and level flight at 100% matched torque has been chosen for the input and main modules because there were no problems attaining this flight condition, and it places these gearboxes under the highest continuous torque. Hover has been chosen for the intermediate and tail rotor gearboxes because it is easily attainable, and places these gearboxes under a moderate-to-high torque. Of the other flight conditions:

a) banked turns were excluded as these were only flown to determine whether turning the aircraft would affect the gearbox vibration, and as it does they are not recommended;

b) forward flight was excluded for the tail rotor gearbox because of extraneous vibration; and

c) tail rotor turns were excluded because they were both physically uncomfortable, and difficult to maintain at a constant rate in a cross-wind.

Table 8. Most Suitable Flight Conditions for Data Acquisition

Gearbox	Flight Condition
Left input module	Straight and Level, 100%/100% matched torque
Right input module	Straight and Level, 100%/100% matched torque
Main module	Straight and Level, 100%/100% matched torque
Intermediate gearbox	Hover
Tail rotor gearbox	Hover

6. Concluding Remarks

A lightweight transmission vibration monitoring system based on a ruggedised portable computer has been developed, constructed, installed, and flight tested in an Australian Army Black Hawk helicopter.

As the system functioned well during the flight trial, and suitable flight conditions for future gearbox vibration analysis have been found, it could now be deployed on one or two helicopters at a regiment for an extended field trial. Such a trial would identify any operational or logistic difficulties that might be experienced with frequent use, and enable sufficient data to be accumulated to set appropriate vibration alarm levels for the Black Hawk fleet.

The system could also be used in a limited ad-hoc basis to monitor problem gearboxes on other aircraft, such as those producing chip warnings, thus enabling a fault database to be built up. This type of analysis would be limited to the temporary installation of transducers on the input and main modules, however, due to the difficulty of running temporary cables to the intermediate and tail rotor gearboxes.

Acknowledgments

The authors wish to acknowledge:

a) Brian Rebbechi and David Forrester for their advice on the development of the system and the analysis of vibration data;

b) Ray Maier for fabricating all of the parts required to construct the system, including the connector interface, expansion card supports, and assorted cables;

c) Dr Rami Reddy for his advice on helicopter main rotor and tail rotor wake aerodynamics; and

d) ARDU for the installation of the system in the aircraft, including the design and fabrication of the tail rotor photocell installation, the modified tail boom fold cable connection, the computer harness, the accelerometer and cable installation, and all the photographs in this report.

References

1 Forrester, B.D., *RAN Vibration Analysis System Operators' Guide*, ARL Propulsion Technical Memorandum 441, 1989.

2 Blunt, D.M., Rebbechi, B., Forrester, B.D. and Vaughan, K.W., *A Portable Transmission Vibration Analysis System for the S-70A-9 Black Hawk Helicopter*, DSTO-TR-0072, AR-008-938, 1994.

3 *Support to AMRL Evaluation of a Portable Vibration Analysis System*, RAAF ARDU Formal Report - Task 0128, 1993.

4 *FieldWorks User Manual*, Fieldworks Inc Technical Publications, 7600 Golden Triangle Drive, Eden Prairie MN 55344 USA.

5 *Techfilter Owners Manual*, Onsite Instruments Inc, 855 Maude Ave #2, Mountain View CA 94043 USA.

6 *User Manual for DT2821 Series*, Data Translation Inc, 100 Locke Drive, Marlboro MA 01752-1192 USA: Document UM-05073-H.

7 *Performance Specification Integral Electronics Accelerometer 6259M6*, Endevco, 30700 Rancho Viejo Road, San Juan Capistrano CA 92675 USA.

8 *Operation and Maintenance Manual for Photocell System PN 10252*, Chadwick-Helmuth Co Inc, 4601 N. Arden Drive, El Monte CA 91731 USA.

9 Forrester, B.D., *Advanced Vibration Analysis Techniques for Fault Detection an Diagnosis in Geared Transmission Systems*, PhD Thesis, Swinburne University of Technology, submitted February 1996.

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Appendix 1
System Database, Parameters, Operation and Software

System Database

Directory Structure

```
C:PVAS
 |
 +---A25                          -Directory for B/Hawk (A25) default files.
 |         INPUTL.INI   ]         Default gearbox INI files for
 |         INPUTR.INI   |         gearboxes in the B/Hawk.
 |         INTER.INI    }         On creating a new gearbox sub-
 |         MAIN.INI     |         directory, copy these files into
 |         TAIL.INI     J         the directory, then edit to suit.
 |         TAILNO.INI   -Default tailno INI file for the B/Hawk.
 |
 +---A25_206                      -Directory for aircraft A25_206.
 |  |      A25_206.INI  -Tailno INI file for A25_206.
 |  |      TSN_206.INI  -Current TSN INI file for A25_206.
 |  |      TSN_206.000  -Previous TSN INI file.
 |  |      TSN_206.001  -TSN file previous to TSN_206.000.
 |  |
 |  +---26403586 -Directory for g'box serial no 26403586
 |  |      |      26403586.INI -INI file for left input module 26403586
 |  |      |      ISL889.AVG   ]      Signal averages, xxxyyy.AVG,
 |  |      |      ISL891.AVG   }      where:
 |  |      |      QSL889.AVG   |             xxx = shaft code
 |  |      |      QSL891.AVG   J             yyy = TSN hours
 |  |      |      LPS889.SPC   -Power spectrum @ 889 hours
 |  |      |      LPS891.SPC   -Power spectrum @ 891 hours
 |  |      |      ISL-206.TND  -Condition index trend file for shaft ISL
 |  |      |      QSL-206.TND  -Condition index trend file for shaft QSL
 |  |      |
 |  |      +---RAWDATA
 |  |                   IML889.206   -Raw data file captured @ 889 hours
 |  |                   IML891.206   -Raw data file captured @ 891 hours
 |  |
 |  +---{other gearbox serial number, eg main, intermediate, tail}
 |
 +---{other tail number}
```

INI Files

INI File	Directory	Contains
TailNo.INI (eg A25_206.INI)	\PVAS\tailno	Information about the aircraft, the gearboxes installed in the aircraft, and the vibration and tachometer channels.
TSN_xxx.INI xxx = last 3 digits of tailno (eg TSN_206.INI)	\PVAS\tailno	Information about the time since overhaul for each gearbox.
SerialNo.INI (eg 26403586.INI)	\PVAS\tailno \serialno	Information about the data acquisition and analysis processes; eg sample rates, filter settings, averaging info, gear ratios, and teeth numbers

Raw Data File ID Codes

Code	Description
IML	Left input module
IMR	Right input module
INT	Intermediate gearbox
TAI	Tail rotor gearbox
MMF	Main module fixed axis gears
MMP	Main module planetary gears

Signal Average File ID Codes

Code	Description	Gearbox
ISL	Input Shaft Left	Left Input Module
QSL	Quill Shaft Left	Left Input Module
ISR	Input Shaft Right	Right Input Module
QSR	Quill Shaft Right	Right Input Module
CAR	Planet Carrier	Main Module
CBP	Combining Pinions	Main Module
CRO	Crownwheel	Main Module
Plx	Planet x (PL1 to PL5)	Main Module
PNT	Composite Planets	Main Module
SUN	Sun	Main Module
TTO	Tail Take Off	Main Module
IIM	Intermediate Input Main Tacho	Intermediate
IIT	Intermediate Input Tail Tacho	Intermediate
IOM	Intermediate Output Main Tacho	Intermediate
IOT	Intermediate Output Main Tacho	Intermediate
TIM	Tail Input Main Tacho	Tail
TIT	Tail Input Tail Tacho	Tail
TOM	Tail Output Main Tacho	Tail
TOT	Tail Output Tail Tacho	Tail

Spectrum File ID Codes

Code	Description	Gearbox
LPS	Left Input Module Power Spectrum	Left Input Module
RPS	Right Input Module Power Spectrum	Right Input Module
MPS	Main Module Power Spectrum	Main Module
IPS	Intermediate Gearbox Power Spectrum	Intermediate
TPS	Tail Gearbox Power Spectrum	Tail

System Parameters

Accelerometer Sensitivities

Location	Serial#	Sensitivity
Left Input Module	AB56	0.009831 V/g
Right Input Module	AB69	0.009909 V/g
Main Module	AB67	0.009894 V/g
Intermediate	AB70	0.010030 V/g
Tail Rotor	AB68	0.009788 V/g

Amplifier Gains

The amplifier gains for each card are listed below. The signal conditioning card gains were set to one step below the highest values that did not overload the anti-aliasing filter card (ie within ±5 Volts). This will have reduced the effective signal-to-noise ratio of the filter output (by 6 dB), but was done for two reasons:

a) To avoid the slight signal distortion introduced by the filter when signals exceed ±4.5 V.

b) To allow some latitude in the actual signal amplitudes. This was desirable because it is easier to adjust the software programmable gains than the DIP switches on the signal conditioning card. This strategy will also allow the system to be transferred between aircraft more easily, as slight differences in the overall gains can be absorbed by the software programmable gains stored in the initialisation files for each aircraft, leaving the DIP switch settings fixed.

The anti-aliasing filter card gains were fixed at unity, and the analogue-to-digital converter gains were set to the highest values that did not overload the converter (ie within ±5 V).

Channel	Sig Cond Gain	AAF Gain	ADC Gain	Description
1	1	1	2	Left Input Module
2	1	1	2	Right Input Module
3	2	1	2	Main Module
4	4	1	2	Intermediate
5	8	1	1/2*	Tail
6	1	1	1	Unused
7	1	1	1	Main Tacho
8	1	1	2	Tail Tacho

* A gain of 2 was used for hover, but this had to be reduced to 1 for forward flight due extraneous vibration, see Section 5.6.3.

Data Acquisition Parameters

Six different data acquisitions were set-up using the five accelerometers and two tachometer signals, with the parameters shown below. The differences in sample rates, filter settings, and sample times reflect the different shaft speeds and gear frequencies in each gearbox.

#	Accelerometer	Tachometer	Sample Rate (Hz)	Filter Cut-Off (Hz)	Time (sec)	File Size (MB)
1	Left Input	Main	70,000	25000	5	1.40
2	Right Input	Main	70,000	25,000	5	1.40
3	Main	Main	24,000	9,000	24	2.30
4	Main	Main	12,000	4,400	61	2.93
5	Intermediate	Main & Tail	22,000	8,000	10	1.32
6	Tail	Main & Tail	14,000	5,000	22	1.85

Data Analysis Parameters

Signal Average	Shaft Parameters*	Gear Parameters*
ISL	/m22	/n22 /b7 /e
QSL	/m21 /m76 /m80	/n160 /b4 /e; /n21 /b7 /e; /n152 /b4 /e
ISR	/m22	/n22 /b7 /e
QSR	/m21 /m76 /m80	/n160 /b4 /e; /n21 /b7 /e; /n152 /b4 /e
CAR	/m5 /m228	/c456 /b9 /e
CBP	/m21 /m76 /m80	/n21 /b10 /e
CRO	/m75 /m100	/n75 /b12 /e; /n100 /b12 /e
PIx	/m83	/n83 /b14 /e
PNT	/m83	/n83 /b14 /e
SUN	/m62	/n62 /b14 /e
TTO	/m22	/n22 /b10 /e
IIM	/m25	/n25 /b14 /e
IIT	/m25	/n25 /b14 /e
IOM	/m31	/c31 /b14 /e
IOT	/m31	/c31 /b14 /e
TIM	/m19	/n19 /b14 /e
TIT	/m19	/n19 /b14 /e
TOM	/m4 /m53	/n53 /b14 /e
TOT	/m4 /m53	/n53 /b14 /e

* /m= remove all multiples of this frequency when computing the residual signal
/r = remove this frequency when computing the residual signal
/n = use the multiple of this frequency with the largest magnitude as the centre frequency for the narrow band analysis
/c = centre frequency for narrow band analysis
/b = band width for narrow band analysis
/e = compute envelope of narrow band signal

System Operation

Adding a New Aircraft

Adding a new aircraft to the database requires the creation of a new branch of the directory structure shown above. That is, a new directory for the aircraft tail number, and new gearbox sub-directories for the gearboxes in that aircraft. The default tail number, TSN, and gearbox INI files need to be copied into the appropriate directories; renamed according to the actual tail number and gearbox serial numbers; then edited to change their default data.

Updating a TSN INI File Prior to Acquiring Data

Prior to acquiring a new set of in-flight vibration data, the TSN INI file for the aircraft must be updated to change the TSNs for each gearbox on that aircraft (eg TSN_206.INI). The TSNs are listed by their corresponding gearbox number (as listed in the tail number INI file). They must be whole numbers. For example, to add 10 hours to each gearbox in the following TSN INI file:

```
[TSN]
TSN1=889
TSN2=889
TSN3=889
TSN4=889
TSN5=1300
```

becomes:

```
[TSN]
TSN1=899
TSN2=899
TSN3=899
TSN4=899
TSN5=1310
```

When the new data are acquired the TSN INI file is copied to a TSN history file. The history files have sequentially numbered extensions (eg TSN_206.003), and the latest history file has the highest extension number.

System Preparation Before Flight

a) If the aircraft to be monitored has not previously been entered into the database, then a new branch of the directory structure must be created for this aircraft.

b) Update the TSNs for the aircraft.

c) Install the computer in the aircraft ensuring that the computer power switch (located under display panel) is off, and the 5 A and 3 A circuit breakers on the connector interface are pulled out.

In Flight System Operation

a) After the engines have been started, and the aircraft power has been switched to the main generators, push the 5 A and 3 A circuit breakers in, and turn the computer on.

b) When the computer has booted, start the data acquisition program by typing the following command at the DOS prompt:

ACQUIRE *TailNo*

(Where *TailNo* is the tail number of the helicopter, eg A25_206)

c) Follow the instructions on the screen to acquire the vibration data. The program will progress through a series of data acquisitions, prompting the operator to press the appropriate function keys on the keyboard when necessary, until all the required data has been collected. Each data acquisition stage consists of waiting until the helicopter is in the appropriate flight condition (displayed on the screen), pressing a function key to start the acquisition, waiting until it is finished, and moving on to the next acquisition. If any errors are encountered during the acquisition, the program will display an error message and prompt the operator to either try again or skip to the next acquisition.

d) After the data acquisition has been completed, exit the acquisition program, turn the computer off, and pull the 5 A and 3 A circuit breakers. This should be done before the helicopter lands.

Post Flight System Operation

a) Remove the computer from the helicopter.

b) Run the data processing program by typing the following command at the DOS prompt:

PROCESS *TailNo*

(Where *TailNo* is the tail number of the helicopter, eg A25_206)

c) Follow the instructions on the screen to process the vibration data. The program will progress through the data previously acquired, prompting the operator to press the appropriate function keys on the keyboard when necessary, until all the data has been processed. Each processing stage consists of computing the desired signal from the raw data file, and storing it in the appropriate directory. If any errors are encountered during the processing, the program will display an error message and prompt the operator to try again or skip to the next data file.

d) Run the data analysis program by typing the following command at the DOS prompt:

ANALYSE *TailNo*

(Where *TailNo* is the tail number of the helicopter, eg A25_206)

e) Follow the instructions on the screen to analyse the processed data. The program will compute the condition indices for each processed signal data file, and append them to the trend file for that signal.

System Software

The four programs used in the system are described below. Each is operated by following the instructions displayed on the screen when running. The available commands appear along the bottom of the screen, and are operated by pressing the corresponding function keys on the computer keyboard.

ACQUIRE.EXE

This program is used to acquire the vibration data in flight. It is invoked by the following command line entered at the DOS prompt:

```
ACQUIRE TailNo
```

Where: TailNo = the aircraft tail number (eg A25_206)

The program reads the tail number INI file (eg A25_206.INI) to discover how many gearboxes there are, then progressively works its way through each gearbox INI file performing the data acquisitions specified therein, getting the TSN for the gearbox from the TSN INI file. Each acquisition is saved with an identifying header in the appropriate gearbox raw data directory with a name made up from its three character ID code (see above), its TSN, and an extension of the last three characters of the tail number (eg IML889.206 for a left input module of A25_206 @ a TSN of 889 hours).

An annotated diagram of the display for this program is shown below. The program is operated by following the instructions in the `INSTRUCTIONS` box. The `DATA ACQUISITION` box shows the acquisition number, flight condition, and other details. The `STATUS` box shows which acquisitions have been completed, what the program is currently doing, and a status bar which moves from left to right while the program is performing a task.

```
 GEARBOX VIBRATION DATA ACQUISITION FOR: BLACK HAWK A25_206
+ INSTRUCTIONS ---------------------------------------------------------------+
| 1. WAIT FOR THE AIRCRAFT TO STABILISE AT THE FLIGHT CONDITION.              |
| 2. PRESS F2 TO ACQUIRE THE CURRENT ACQUISITION.                             |
| 3. PRESS F4/F6 TO SELECT THE NEXT/PREVIOUS ACQUISITION.                     |
| 4. REPEAT UNTIL ALL ACQUISITIONS ARE COMPLETED.                             |
+-----------------------------------------------------------------------------+
+ DATA ACQUISITION ------------------------  Acquisition no. (changes each time F4 or F6 is
|ACQUISITION:     1 OF 9  <---------------
|FLIGHT CONDITION: 100%/100% Torque Straight and Level  <-- Flight condition for acquisition
|---------------------------------------------------------------
|GEARBOX:      Left Input Module                                              |
|SERIAL NO:    26403586                    TSN:          888                  |
|                                                                             |
|SAMPLE RATE: 71428.57                     TIME:         5.0                  |
|BANDWIDTH:   25000.00                     CHANNELS:     1, 7                 |
+-----------------------------------------------------------------------------+
+ STATUS -------------------------------------------  Acquisitions already completed
|ACQUISITIONS COMPLETED: 1  <-----------------------
|                  Status bar displayed here during acquisition
|                                                    Press F8 to preview signals
|                                                    with an oscilloscope function
+------------------------- Press F4 for next acquisition ----------------------+
F1       F2       F3       F4       F5       F6       F7       F8       F9       F10
         ACQUIRE           NEXT              PREV              O'SCOPE           EXIT
     Press F2 to start acquisition   Press F6 for previous acquisition   Press F10 to exit
```

PROCESS.EXE

This program is used to process the vibration data acquired in-flight. It is invoked by the following command line entered at the DOS prompt:

```
PROCESS TailNo
```

Where: TailNo = the aircraft tail number (eg A25_206)

The program progressively works its way through each gearbox computing the signals specified in the gearbox INI file. Processed data are saved in the appropriate gearbox's directory with a name made up from its three character ID code (see above), its TSN, and an extension identifying the type of data (eg ISL889.AVG for a left input shaft signal average @ a TSN of 889 hours).

An annotated diagram of the display for this program is shown below.

```
 PROCESS GEARBOX VIBRATION DATA FOR:  BLACK HAWK A25_206
+ INSTRUCTIONS -------------------------------------------------------------+
| 1. PRESS F2/F3 TO COMPUTE CURRENT/ALL SIGNALS.                            |
| 3. PRESS F5/F6 TO SELECT THE NEXT/PREVIOUS SIGNAL.                        |
| 4. REPEAT UNTIL ALL SIGNALS ARE COMPLETED.                                |
+---------------------------------------------------------------------------+
+ DATA FILE: C:\PVAS\A25_206\26403586\RAWDATA\IML888.206 -------------------+
|GEARBOX:     Left Input Module                                             |
|SERIAL NO:   26403586                   TSN:          888                  |
|SAMPLE RATE: 71428.57                   TIME:         5.0                  |
|BANDWIDTH:   25000.00                   CHANNELS:     1, 7                 |
+---------------------------------------------------------------------------+
+ SIGNAL -------------------------------------------------------------------+
|Signal:      1 of 24                    Type:         AVERAGE              |
|Signal ID:   ISL                        Points:       256                  |
|R1/R2:       185/209                    Averages:     400                  |
+---------------------------------------------------------------------------+
+ STATUS -------------------------------------------------------------------+
|SIGNALS DONE:                                                              |
|                                                                           |
|                                                                           |
|                                                                           |
+---------------------------------------------------------------------------+
F1      F2      F3      F4      F5      F6      F7      F8      F9      F10
        CURR    ALL             NEXT    PREV    GBOX                    EXIT
```

Signal no. (changes each time F5 or F6 is pressed)

Signals already

Status bar displayed here during processing.

Press F5 for next

Press F7 to skip to next

Press F2 to compute current signal.

Press F3 to compute all signals.

Press F6 for previous

Press F10 to exit.

ANALYSE.EXE

This program is used to analyse the processed vibration data. It is invoked by the following command line entered at the DOS prompt:

```
ANALYSE TailNo
```

Where: TailNo = the aircraft tail number (eg A25_206)

The program progressively works its way through each gearbox performing the data analysis specified in the gearbox INI file (ie computing the condition indices). Analysed data are appended to the appropriate trend file which is saved in the gearbox directory with a name made up from its three character ID code (see above) and the last three digits of the tail number (eg ISL-206.TND for the trend file of the left input shaft).

An annotated diagram of the display for this program is shown below.

```
 ANALYSE GEARBOX VIBRATION DATA FOR:   BLACK HAWK A25_206
+ INSTRUCTIONS -----------------------------------------------------------------+
¦ 1. PRESS F2/F3 TO ANALYSE CURRENT/ALL SIGNAL.                                 ¦
¦ 2. PRESS F5/F6 TO SELECT THE NEXT/PREVIOUS SIGNAL.                            ¦
¦ 3. REPEAT UNTIL ALL SIGNALS ARE ANALYSED.                                     ¦
+-------------------------------------------------------------------------------+
+ GEARBOX INFO -----------------------------------------------------------------+
¦Gearbox:      Left Input Module                                                ¦
¦Serial No:    26403586                    TSN:         891                     ¦
+-------------------------------------------------------------------------------+
+ SIGNAL: C:\PVAS\A25_206E\26403586\ISL891.AVG ---------------------------------+
¦Signal:       1 OF 28                     Type:                                ¦
¦Signal ID:    ISL                         Points:      256                     ¦
¦R1 / R2:      185 / 209                   Averages:    400                     ¦
¦Res. Params:  /m22                                                             ¦
¦NB. Params:   /n22 /b7 /e;                                                     ¦
+-------------------------------------------------------------------------------+
+ STATUS -----------------------------------------------------------------------+
¦SIG'S ANALYSED:1 2 3                                                           ¦
¦                                                                               ¦
¦                                                                               ¦
¦                                                                               ¦
+-------------------------------------------------------------------------------+
F1       F2       F3       F4       F5       F6       F7       F8       F9       F10
         CURR     ALL               NEXT     PREV     GBOX                       EXIT
```

Signal no. (changes each time F5 or F6 is pressed)

Signals already

Status bar displayed here during processing.

Press F5 for next

Press F7 to skip to next

Press F2 to analyse current signal.

Press F3 to analyse all signals.

Press F6 for previous

Press F10 to exit.

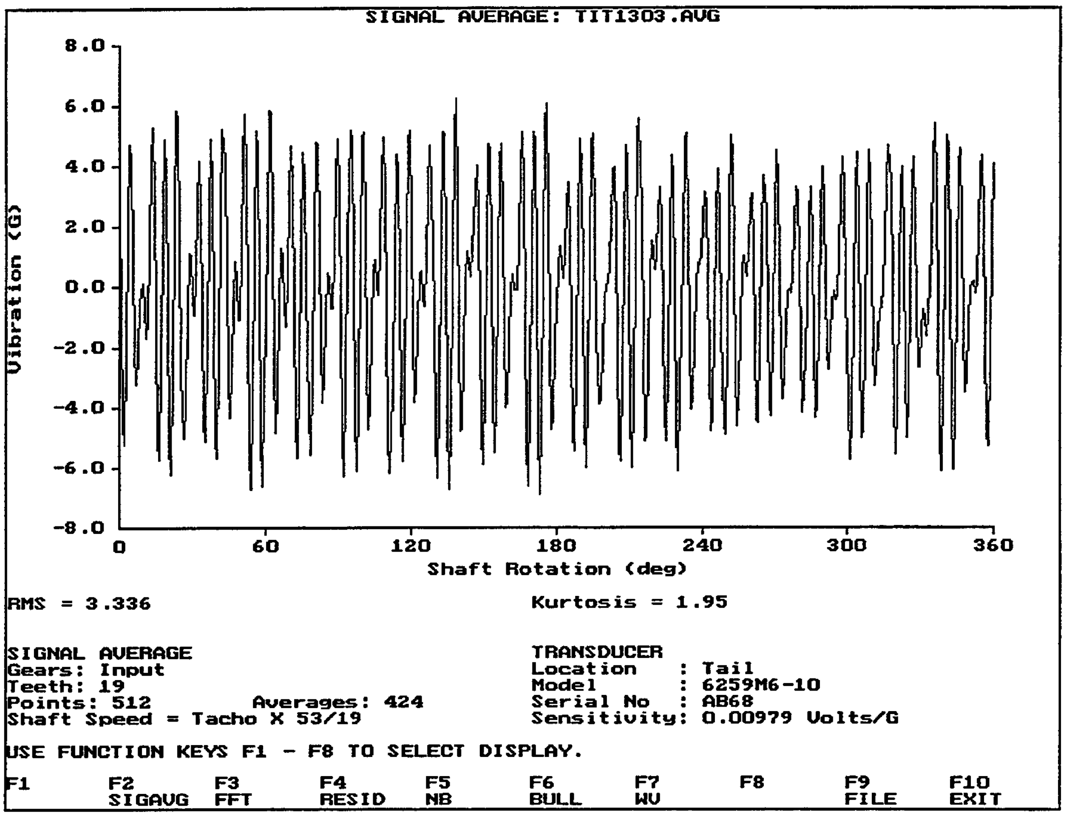
VIEW.EXE

This program is used to view the vibration data. It is invoked by the following command line entered at the DOS prompt:

```
VIEW TailNo
```

Where: TailNo = the aircraft tail number (eg A25_206)

After typing the command line, the user is prompted to select the gearbox and signal to view. The program then brings up the display shown below. The function keys allow the user to view the signal in various ways, including FFT, residual signal, narrow band signal, bullseye, and Wigner-Ville displays.



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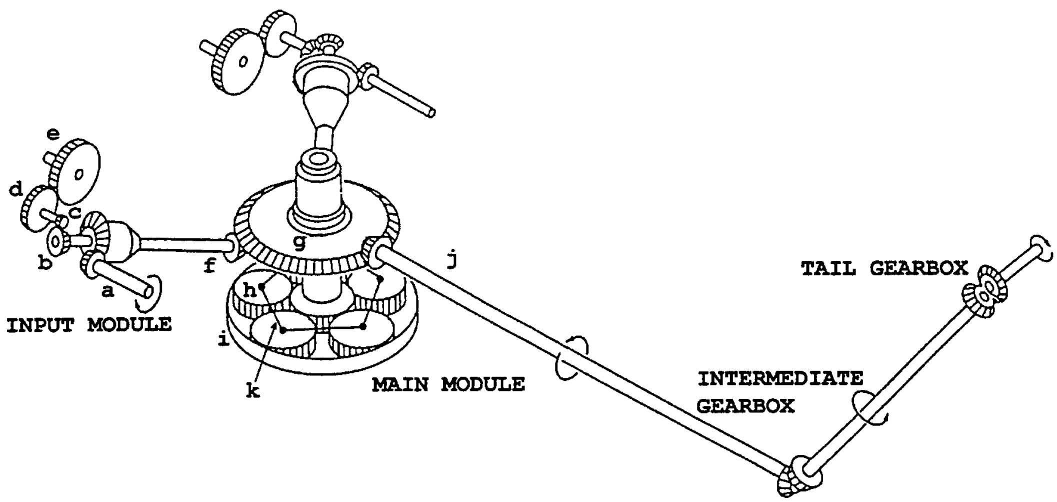
Appendix 2
Black Hawk Gearbox Schematic



Shaft	RPM	Gear	Teeth	Mesh Freq(Hz)
Input Module				
a High Speed Input Shaft	20900	Input Pinion	22	7663
b Input Gear Shaft	5748	Input Gear	80	7663
		Accessory Drive Take-off	76	7281
c Accessory Drive Shaft	11806	Accessory Drive Gear	37	7281
Accessory Module				
d Generator Drive Shaft	11806	Hydraulic Drive Take-off	56	11019
e Hydraulic Drive Shaft	7186	Hydraulic Drive Gear	92	11019
Main Module				
f Combining Pinion Shaft	5748	Combining Pinion	21	2012
g Crownwheel Shaft	1207	Lower Crownwheel Gear	100	2012
		Upper Crownwheel Gear	75	1509
		Sun Gear	62	980
h Planet Gear (wrt Carrier)	708	Planet Gear	83	980
i Ring Gear	0	Ring Gear	228	980
j Tail Drive Shaft	4115	Tail Take-off	22	1509
k Planet Carrier/ Main Rotor	258	Lube Pump Take-off	152	654
Lube Pump Drive Shaft	3268	Lube Pump Drive Gear	12	654
Intermediate Gearbox				
l Input	4115	Input Pinion	25	1714
m Output	3318	Output Gear	31	1714
Tail Rotor Gearbox				
n Input	3318	Input Pinion	19	1051
o Output	1190	Output Gear	53	1051

Appendix 3
Black Hawk Gearbox Vibration Data Acquisition Parameters

The sample rates, filter cut-off settings, and acquisition times for each gearbox are derived below. Selections have been derived on the following guidelines:

a) Filter cut-off settings have been selected to encompass three to four gear mesh harmonics.

b) Sample rates have been set to 2.66 times the filter cut-off frequencies.

c) The number of points-per-revolution for the signal averages have been selected to give effective sampling rates higher than the actual sampling rates to avoid aliasing when calculating the signal averages.

d) Where possible, the number of revolutions averaged during signal averaging have been selected so that the mating gear teeth on the adjacent shafts will have meshed an equal number of times with the gear teeth on the shaft of interest. This is done to average out the effect of these gears on the signal average. Where this cannot be done for every gear because an excessive number of averages would be required, the less important gear mesh, or meshes, have been ignored.

Input & Accessory Modules

Shaft & Mesh Frequencies & Effective Sampling Rates

Shaft	Shaft Freq (Hz)	Teeth	Mesh Freq's (Hz)	Effective Sampling Rates (Hz)		
				512 pts/rev	1024 pts/rev	2048 pts/rev
Input Pinion	348.33	22	7663	**178,345**	356,690	713,380
Input Gear	95.8	80,76,21	7663, 7281, 2012	49,050	**98,099**	196,198
Generator	197	37,56	7281, 11019	**100,864**	201,728	403,456
Hydraulic	120	92	11019	61,440	**122,880**	245,760

Due to the high gear mesh frequencies, use a filter cut-off frequency of 25 kHz (max available) to capture as many harmonics as possible. Set the sampling frequency to 25 x 2.66 = 66.5, say 70 kHz. Use 512 point signal averages for the Input Pinion and Generator Drive shafts, 1024 points for the rest.

Gear Ratios & Desirable Revolution Multiples for Signal Averages*

Shaft	Meshes	Gear Ratios	Rev Multiple	Period (s)
Input Pinion	1	11/40	**40**	0.12
Input Gear	3 2	40/11, 76/37, 21/100 40/11, 76/37	11 x 37 x 100 = 40700 **11 x 37 = 407**	425 4.25
Generator Drive	2 1	37/76, 14/23 37/76	76 x 23 = 1748 **76**	8.87 0.39
Hydraulic Drive	1	23/14	**14**	0.12

* Shaft revolution multiples required to ensure that all gear teeth on the shaft mesh an equal number of times with their mating gear teeth.

Use the revolution multiples in bold text, as the larger revolution multiples require sample times that are too long. For the Input Gear shaft this ignores the combining pinion mesh, which is in the main module, and for the Generator Drive shaft this ignores the hydraulic drive gear mesh, which has lower tooth loading. A sample time of 5 seconds will be sufficient for 407 rev's of the slowest shaft (Input Gear Shaft).

Filter & A/D Board Settings

Filter (Hz)	Sample Rate / Chan (Hz)	Sample Period (s)	Bytes / Chan
25,000	70,000	5	700,000

Signal Average Parameters

Shaft	Points	Rev's	Ratio To Tacho
Input Pinion	512	400	1/2 x 37/76 x 80/22 = 185/209
Input Gear	1024	407	1/2 x 37/76 = 37/152
Generator Drive	512	532	1/2
Hydraulic Drive	1024	490	1/2 x 56/92 = 7/23

Main Module Fixed Axis Shafts

Shaft & Mesh Frequencies & Effective Sampling Rates

Shaft	Shaft Freq	Teeth	Mesh Freq's	Effective Sampling Rates (Hz)		
	(Hz)		(Hz)	512 pts/rev	1024 pts/rev	2048 pts/rev
Comb Pinion	95.8	80,76,21	7663, 7281, 2012	**49,050**	98,099	196,198
Crown-wheel	20.1	100,75	2012, 1509	10,291	20,582	**41,165**
Tail Take-off	68.6	22,25	1509, 1715	**35,123**	70,246	140,493
Lube Pumps	54.5	12	654	**27,904**	55,808	111,616

Apart from the higher mesh frequencies on the combining pinion shafts, which occur in the input modules and are better represented by the input module accelerometers anyway, a filter setting of 9000 Hz will pass at least three harmonics of the mesh frequencies (9000/2012 = 4.47). Set the sampling frequency to 9000 x 2.66 = 23.9, say 24 kHz. Use 512 point signal averages for all shafts except the Crown-wheel gear shaft which requires 2048 points to get an effective sampling rate higher than 24 kHz.

Gear Ratios & Desirable Revolution Multiples for Signal Averages*

Shaft	Meshes	Gear Ratios	Rev Multiple	Period (s)
Comb. Pinion	3 1	40/11, 76/37, 21/100 21/100	11 x 37 x 100 = 40700 **100**	425 1.04
Crown-wheel	2	100/21, 75/22	21 x 22 = **462**	23
Tail Take-off	2 1	22/75, 25/31 22/75	75 x 31 = 2325 **75**	34 1.09
Lube Pumps	1	12/152	**152**	2.79

* Shaft revolution multiples required to ensure that all gear teeth on the shaft mesh an equal number of times with their mating gear teeth.

Use the revolution multiples in bold text. For the Combining Pinion shafts this ignores the meshes within the input modules, and for the Tail Take-off shaft this ignores the mesh in the intermediate gearbox. A sample time of 24 seconds will be sufficient for 462 rev's of the slowest shaft (Crown-wheel Gear Shaft).

Filter & A/D Board Settings

Filter (Hz)	Sample Rate / Chan (Hz)	Sample Period (s)	Bytes / Chan
9,000	24,000	24	1,152,000

Signal Average Parameters

Shaft	Points	Rev's	Ratio To Tacho
Comb. Pinion	512	500	1/2 x 37/76 = 37/152
Crown-wheel	1024	462	1/2 x 37/76 x 21/100 = 777/15200
Tail Take-off	512	450	1/2 x 37/76 x 21/100 x 75/22 = 58275/334400 = 2331/13376
Lube Pumps	512	608	1/2 x 37/76 x 21/100 x 62/(228+62) x 152/12 = 152551/1102000

Main Module Planetary Gears

Shaft & Mesh Frequencies & Effective Sampling Rates

Shaft	Shaft Freq	Mesh Freq's	Effective Sampling Rates (Hz)		
	(Hz)	(Hz)	1024 pts/rev	2048 pts/rev	4096 pts/rev
Planet Carrier (ring gear)	4.3	980	4,403	8,806	**17,613**
Sun wrt carrier	15.8	980	**16,179**	32,358	64,716
Planets wrt carrier	11.8	980	**12,083**	24,166	48,332

A filter setting of 4400 Hz will pass 4.5 mesh harmonics. Set the sampling frequency to $4400 \times 2.66 = 11704$, say 12000 Hz. Use 4096 points for the Planet Carrier signal average, 1024 points for the others.

Desirable Revolution Multiples for Planetary Signal Averages*

Shaft	Teeth	Modulation Removed	Rev Multiple	Period (s)
Planet Carrier (ring gear)	228	Planets and Planet-pass	**83**	19.3
Sun	62	Planet-pass	**114 rev's of sun wrt PC** (145 rev's of sun) 114 x 62/228 = **31 rev's of PC**	7.21
Sun	62	All	228 x 83 = 18924 rev's of sun wrt PC 18924 x 62/228 = 5146 rev's of PC	1197
Planets	83	Planet-pass	**228 rev's of planets wrt PC** 228 x 83/228 = **83 rev's of PC**	19.3
Planets	83	All	228x62=14136 rev's of planets wrt PC 14136 x 83/228 = 5146 rev's of PC	1197

* Shaft revolution multiples required to ensure that all gear teeth on the shaft mesh an equal number of times with their mating gear teeth.

To remove all modulation from every average would require a sample period that is too long (nearly 20 min). Therefore, only the planet-pass modulation is removed. A sample time of 60 seconds will be sufficient for 249 rev's of the Planet Carrier.

Filter & A/D Board Settings

Filter (Hz)	Sample Rate / Chan (Hz)	Sample Period (s)	Bytes / Chan
4,400	12,000	61	1,464,000

Signal Average Parameters

Shaft	Points	Rev's wrt PC	Ratio of Shaft Freq (WRT Planet Carrier) To Tacho
Planet Carrier	2048	249	1/2 x 37/76 x 21/100 x 62/(228+62) = 24087/2204000
Sun	1024	684	1/2 x 37/76 x 21/100 x 228/(228+62) = 44289/1102000
Planets	1024	684	1/2 x 37/76 x 21/100 x 228/83 x 62/(228+62) = 1372959/45733000

Intermediate Gearbox

Shaft & Mesh Frequencies & Effective Sampling Rates

Shaft	Shaft Freq (Hz)	Teeth	Mesh Freq's (Hz)	Effective Sampling Rates (Hz) 512 pts/rev	1024 pts/rev	2048 pts/rev
Input	68.6	25	1714	35123	70246	140493
Output	55.3	31	1714	28313	56627	113254

To capture 4 harmonics of the mesh frequency, set the filter to 8000 Hz and sample at 8000 x 2.66 = 21280, say 22000 Hz. Use 512 point signal averages.

Gear Ratios & Desirable Revolution Multiples for Signal Averages*

Shaft	Meshes	Gear Ratios	Rev Multiple	Period (s)
Input	1	25/31	31	0.451
Output	1	31/25	25	0.451

* Shaft revolution multiples required to ensure that all gear teeth on the shaft mesh an equal number of times with their mating gear teeth.

A sample time of 10 seconds will be sufficient for 450 rev's of the Output shaft.

Filter & A/D Board Settings

Filter (Hz)	Sample Rate / Chan (Hz)	Sample Period (s)	Bytes / Chan
8000	22000	10	440,000

Signal Average Parameters

Shaft	Points	Rev's	Ratio To 115VAC Tacho	Ratio to Tail Tacho
Input	512	465	1/2 x 37/76 x 21/100 x 75/22 = 2331/13376	53/19 x 31/25 = 1643/475
Output	512	450	1/2 x 37/76 x 21/100 x 75/22 x 25/31 = 58275/414656	53/19

Tail Rotor Gearbox

Shaft & Mesh Frequencies & Effective Sampling Rates

Shaft	Shaft Freq (Hz)	Teeth	Mesh Freq's (Hz)	Effective Sampling Rates (Hz)		
				512 pts/rev	1024 pts/rev	2048 pts/rev
Input	55.3	19	1051	**28313**	56627	113254
Output	19.8	53	1051	10137	**20275**	40550

To capture 4 harmonics of the mesh frequency, set the filter to 5000 Hz and sample at 5000x2.66=13300, say 14000 Hz. Use 512 point signal average for the input shaft, 1024 for the output shaft.

Gear Ratios & Desirable Revolution Multiples for Signal Averages*

Shaft	Meshes	Gear Ratios	Rev Multiple	Period (s)
Input	1	19/53	**53**	0.958
Output	1	53/19	**19**	0.958

* Shaft revolution multiples required to ensure that all gear teeth on the shaft mesh an equal number of times with their mating gear teeth.

A sample time of 22 seconds will be sufficient for 399 rev's of the Output shaft.

Filter & A/D Board Settings

Filter (Hz)	Sample Rate / Chan (Hz)	Sample Period (s)	Bytes / Chan
5000	14000	22	616,000

Signal Average Parameters

Shaft	Points	Rev's	Ratio To 115VAC Tacho	Ratio to Tail Tacho
Input	512	424	1/2 x 37/76 x 21/100 x 75/22 x 25/31 = 58275/414656	53/19
Output	1024	399	1/2 x 37/76 x 21/100 x 75/22 x 25/31 x 19/53 = 1107225/21976768	1/1

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D.M. Blunt and S.A. Dutton

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19. ABSTRACT

A lightweight carry-on/carry-off transmission vibration monitoring system has been developed for the Black Hawk helicopter. The system collects vibration data from accelerometers mounted on the transmission while in flight, and then post-processes the data on the ground using AMRL-developed fault detection algorithms. This report describes the system, its installation and operation, and the results of a flight trial conducted by the RAAF Aircraft Research and Development Unit.